Fisheries

# Stock assessment of Australian Sardine (*Sardinops sagax*) off South Australia 2025


Bailleul, F., Ivey, A. R., Grammer, G. L. and Earl, J.



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December 2025

Report to PIRSA Fisheries and Aquaculture

Government of South Australia
Department of Primary Industries and Regions

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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**December 2025**

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*We ensure the land, sea, water and sky are healthy for future generations and strive to better understand their spiritual and cultural significance for Aboriginal people across the state.*

*In the spirit of reconciliation, our commitment is to build progressive and trusting relationships, to share knowledge and learn from each other.*

*We recognise and own a difficult past, and together we will walk forward.*

*We acknowledge the many Aboriginal people of this Country as the oldest continuous living culture in the world.*

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# EXECUTIVE SUMMARY

## Overview

This report assesses the status of the stock of Australian Sardine (*Sardinops sagax)* off South Australia. It informs management of the South Australian Sardine Fishery (SASF), which was established in 1991 and is Australia's largest fishery by weight. The SASF is a purse-seine fishery with limited entry. The primary management tool is the Total Allowable Commercial Catch (TACC). The key performance indicator is the estimate of spawning biomass obtained using the Daily Egg Production Method (DEPM).

Stock status is linked prescriptively to reference points specified for the spawning biomass within the harvest strategy in the Management Plan for the fishery (PIRSA 2023). A TACC is set by applying precautionary exploitation rates of 12.5 to 27.5%, based on decision rules relating to the size of the spawning biomass in the Spencer Gulf (SG) Zone and Gulf St Vincent (GSV) Zone, and the level of research and monitoring undertaken (i.e. frequency of application of the DEPM, population modelling and ecosystem assessment), with annual catch caps in place for both Zones.

## Uncertainty in the assessment

Key uncertainties in this stock assessment include those associated with ageing Australian Sardine from otolith growth increments, and the lack of age composition data for 2025. These limitations reduce confidence in the stock status classification. In addition, the assessment incorporates data up to April 2025, and therefore does not account for potential effects of the significant algal bloom– first occurring in coastal waters off the Fleurieu Peninsula in March 2025, and subsequently expanding to Investigator Strait, Gulf St Vincent and Spencer Gulf in April 2025—on the Australian Sardine stock. Notably, (1) extensive and widespread mortalities of finfish, elasmobranchs, cephalopods, and crustaceans have been reported, but not for Australian Sardine, and (2) substantial changes in fisher behaviour, catches and effort have occurred in 2025 (SARDI unpublished data). The impact of these mortalities and changes in fishing practices on the Australian Sardine stock and fishery have not yet been quantified.

## Stock status

During February–April 1995, the spawning biomass of Sardine off South Australia (obtained using the DEPM) was estimated to be approximately 320,000 t. Although mass mortality events in 1995 and 1998 reduced the spawning biomass to less than 100,000 t in both 1996 and 1999, the stock recovered quickly. Since 2006, the spawning biomass has been above ~200,000 t. In 2024, the estimate of spawning biomass (95% CI) for Sardine off South Australia obtained using the DEPM was 291,731 (248,230–335,232) t (Grammer et al. 2024a). The estimate of spawning biomass from the February–April 2025 DEPM survey was 556,957 t (474,724–639,191 t) (Ivey et al. 2025).

The total annual catch of Sardine recorded in Catch Disposal Records was below 8,000 t until 2001. Catches increased rapidly after 2002, reaching ~42,500 t in 2005. Catches were between ~38,600 and ~40,800 t during 2019–2021, increased to ~47,400 t in 2022, and were ~45,600 t in 2023 and ~48,500 t in 2024.

The catch from the SG Zone was capped at 30,000 t from 2016 to 2019. The quota for this zone was reduced to 27,000 t in 2020 after the mean size fell below the reference level in 2019; it was increased to 30,000 t in 2021, where it remained in 2022–2024. The catch from the Outside Zone increased from ~1,460 t in 2010 to ~12,300 t in 2017, declined to ~5,700 t in 2021, and then increased to ~11,200 t in 2024. Catches from the GSV Zone have been small, exceeding 1,000 t only in 2005, 2006, 2010 and 2016 (~1,300–2,500 t). Following new TACC provisions in 2020, GSV catches rose to ~5,800 t, then ranged between ~3,300 and ~5,700 t from 2021 to 2024.

The SardEst integrated population assessment model was fitted to annual estimates of spawning biomass (DEPM) and age-composition. Model outputs provided estimates of key management quantities, including spawning biomass, recruitment, harvest fraction, total biomass, and relative depletion. SardEst generally fitted well to observed spawning biomass and age composition data. The model estimated total biomass (including juveniles) at ~723,000 t (±110,000 t) in 1992, and ~244,000 t (±18,000 t) in 1996. Modelled spawning biomass was ~350,000 t (±26,000 t) in 2024 and ~477,000 t (±36,000 t) in 2025, corresponding to exploitation rates of 17% and 12%, respectively.

The estimates of spawning biomass obtained using the DEPM (556,957 t) and from SardEst (~477,000 t) for 2025 were above the target reference point of 200,000 t identified in the Management Plan (PIRSA 2023). Under the criteria outlined in the harvest strategy for the SASF (PIRSA 2023), the Southern Australia stock of Australian Sardine in 2025 is classified as **Sustainable.**

| **Statistic** | **2025** | **2024** | **2023** | **2022** | **2021** |
|---|---|---|---|---|---|
| TACC | 50,000 t | 50,000 t | 50,000 t | 45,000 t | 42,750 t |
| Spawning Biomass (DEPM) | 556,957 t | 291,731 t | 321,854 t | 373,324 t | |
| Spawning Biomass (Model) | 477,000 t | 350,000 t | 313,000 t | 355,000 t | 390,000 t |
| Status | **Sustainable** | **Sustainable** | **Sustainable** | **Sustainable** | **Sustainable** |

**Keywords:** Daily Egg Production Method, spawning biomass, pelagic fishes, spawning fraction, egg production, SardEst.

# 1. INTRODUCTION

## 1.1 Overview

Stock assessment reports on the South Australian Sardine Fishery (SASF) have been published annually or biennially since 1999 (Ward and McLeay 1999). Since 2005, the reports have used age-structure models to integrate fishery-dependent and fishery-independent data (Ward et al. 2005). The aims of this report are to: 1) summarise relevant scientific information on Sardine (*Sardinops sagax)* and describe the history of the SASF (Chapter 1); 2) summarise available catch and effort data (Chapter 2); 3) present age structures and reproductive information (Chapter 3); 4) present the revised time series of fishery-independent estimates of spawning biomass from 1995 to 2025 based on the recommendations of Ward et al. (2021), and incorporate data from the 2024 and 2025 DEPM surveys (Grammer et al. 2024a, Ivey et al. 2025) (Chapter 4); 5) apply SardEst, a stock assessment model developed specifically for the SASF, to integrate fishery-independent and -dependent data (Chapter 5); and 6) assess the status of the stock, and identify future research needs (Chapter 6).

## 1.2 Sardine fisheries, biomass fluctuations and stock structure

Sardine, *Sardinops sagax* (Jenyns 1842), occurs off the west coasts of North and South America, off southern Africa, around Japan and off the southern coasts Australia and New Zealand (Parrish et al. 1989, Grant and Leslie 1996, Grant et al. 1998). The Standard Fish Names List for Australia specifies that the common name for *Sardinops sagax* is Australian Sardine. In this report we use the term Sardine to refer to *S. sagax* in Australia and elsewhere.

Sardine has supported important commercial fisheries throughout its global range where biomass and catches have fluctuated dramatically over multi-decadal scales (e.g. Schwartzlose et al. 1999). For example, the sardine biomass off California peaked at just over 4 million tonnes in the 1930s and declined to <3,000 tonnes in the 1970s (Schwartzlose et al. 1999). Similarly, the Japanese catch peaked at 5.4 million tonnes in 1988 but declined to 0.3 million tonnes in 1996 (Schwartzlose et al. 1999). Recently, the biomass and catches of Sardine off the west coasts of North America (Akselrud et al. 2025) and southern Africa (https://sapfia.org.za/tac/) have been historically low.

Fluctuations in the biomass and catches of Sardine in the Benguela, Californian and Humboldt Current systems off the west coasts of southern Africa and North and South America, respectively, have occurred synchronously (Schwartzlose et al. 1999, Tourre et al. 2007). During periods of low Sardine biomass, the local species of Anchovy (*Engraulis* spp.) has replaced Sardine as the dominant species of small pelagic fish (Schwartzlose et al. 1999). ‘Global synchrony’ in the fluctuations in the relative biomass of Sardine and Anchovy appear to have been driven by multi-decadal changes in global ocean conditions (Schwartzlose et al. 1999, Tourre et al. 2007, Checkley et al. 2017).

The multi-decadal fluctuations in the relative biomass of Sardine and Anchovy that have been recorded elsewhere have not been observed off southern Australia (Schwartzlose et al. 1999, Ward et al. 2001a, Ivey et al. 2025). Sardine is the dominant clupeoid in this region, occurring throughout coastal and shelf waters. In contrast, Anchovy (*Engraulis australis*) is confined mainly to inshore waters (Schwartzlose et al. 1999, Ward et al. 2001a, Dimmlich et al. 2004, 2009, Dimmlich and Ward 2006). The severe Sardine mortality events of 1995 and 1998/99, which have killed more than 50% of the adult population and affected a larger area than any previously recorded fish-kill, reduced Sardine biomass off southern Australia and were followed by an expansion of Anchovy into shelf waters that were previously dominated by Sardine (Jones et al. 1997; Ward et al. 2001a, 2001b). This finding suggests that the fluctuations in relative biomass of Sardine and Anchovy observed globally may also be possible in Australian waters (Ward et al. 2001a, 2001b).

The rapid spread of the 1995 and 1998/99 mortality events across southern Australia (caused by a herpesvirus; Whittington et al. 2008) demonstrated the connectivity of Sardine across this entire geographical range (Whittington et al. 2008). Despite this connectivity, Sardine off southern Australia are considered to be a meta-population (Whittington et al. 2008) comprising four biological stocks (Izzo et al. 2017, Sexton et al. 2019, Ward et al. 2023). The south-western stock occurs off Western Australia, the southern stock off South Australia; the south-eastern stock off Victoria, Tasmania and southern NSW; and the eastern stock off central New South Wales and southern Queensland. There is some evidence to suggest that the south-western and eastern stocks each include two separate sub-components (Gaughan et al. 2002, Izzo et al. 2017, Sexton et al. 2019).

Commercial fishing for Sardine has been conducted off southern Australia since the 1800s (Kailola et al. 1993), but combined national catches had not exceeded 1,000 t until the 1970s. Catches off eastern Australia remained below 500 t until 2003/04, before reaching a peak of almost 5,000 t in 2008/09 and then declining to <1,000 per annum from 2011/12 onwards (Roelofs et al. 2024). Several fisheries for Sardine developed off south-western Australia during the late 1970s (Newman et al. 2023). The total annual catch for Western Australia peaked at ~8,000 t in 1990 but has not exceeded 3,000 t since the mid-2000s, when the stock recovered from the mass mortality events of the 1990s (Newman et al. 2023, Ward et al. 2001b). The SASF was established in 1991 (Ward and Staunton-Smith 2002), and grew rapidly, with the total annual catch exceeding 38,000 t since 2017 (Grammer et al. 2024b).

### 1.3 Biology and ecological importance

The biology of Sardine has been studied extensively in Australia and elsewhere. Sardine is a short-lived (<10 years), fast-growing and highly fecund fish (e.g. Ganias et al. 2012). Growth increments in sagittal otoliths (ear bones) have been widely used to estimate age (Butler et al. 1996, Fletcher and Blight 1996, Rogers et al. 2003). Despite difficulties associated with interpreting and counting opaque and translucent zones (Butler et al. 1996, Fletcher and Blight 1996, Rogers and Ward 2007), there is evidence that Sardines grow faster and reach larger sizes in the productive boundary currents off Africa and North America than they do in the less productive waters off southern Australia (e.g. Fletcher and Blight 1996, Ward et al. 2006). Size, age and growth information for Sardines off South Australia are presented in Chapters 2 and 3 of this report.

Australian Sardines are serial spawners with asynchronous oocyte development and indeterminate fecundity (e.g. Ganias et al. 2012). Females release numerous batches of pelagic eggs throughout a spawning season that typically extends for several months (Lasker 1985). Approximately 10-12% of females spawn each night during the peak spawning season (Ganias et al. 2012). The number of eggs in a batch, i.e. batch fecundity, is correlated with female size (Lasker 1985). In Australia, Sardine usually spawn in shelf waters (Blackburn 1950, Fletcher and Tregonning 1992, Fletcher et al. 1994). The timing of spawning varies between locations; off South Australia the peak spawning season occurs during January to April (Ward et al. 2001a, 2001b, Ward and Staunton-Smith 2002). Information on the reproductive biology of Sardine off South Australia is provided in Chapters 3 and 4 of this report.

Sardines are planktivores (Espinoza et al. 2009). They have two feeding modes: filter-feeding on micro-zooplankton and phytoplankton and particulate-feeding on macro-zooplankton. Sardine switches between these two modes depending on relative prey density (Van der Lingen 1994, 2002, Louw et al. 1998). Off South Australia, Sardine appears to feed mainly on crustaceans, fish eggs and larvae and gelatinous zooplankton (Daly 2007).

Sardines are an important food source for many predatory fishes, squid, seabirds and marine mammals (e.g. Pikitch et al. 2012). However, the reliance of predators on Sardine and other small pelagic fishes varies among ecosystems and species (e.g. Smith et al. 2011, Hilborne et al. 2017). The trophic role of sardines is particularly important in ‘wasp-waisted’ ecosystems, such as those found in the productive California, Humboldt and Benguela Current systems where one or two species usually dominate the pelagic fish biomass (e.g. Cury et al. 2000). In contrast, several studies have shown that Australia’s less productive pelagic ecosystems support a wide range of small- to medium-sized planktivores, and that few predators are highly dependent on a single prey species (Bulman et al. 2011, Smith et al. 2015). Off South Australia, marine predators feed opportunistically on a wide range of prey species (Goldsworthy et al. 2013). While, no predators have been shown to be solely dependent on Sardine as a food source, crested terns rely on them as a major food source during the breeding season (McLeay et al. 2009a, 2009b, Goldsworthy et al. 2013).

## 1.4 The South Australian Sardine Fishery

The SASF is managed by the *Fisheries Management (Sardine Fishery) Regulations 2021* and *Fisheries Management Act 2007*. Management goals for the SASF are consistent with the objectives of the *Fisheries Management Act 2007* and are outlined in the current Management Plan (PIRSA 2023). Management measures include entry limitations, gear restrictions and individual transferable quotas. Purse-seine nets must not exceed 1,000 m in length or 200 m depth. There are 14 licences with several companies operating multiple licences. The costs of the policy, compliance and research programs that are needed to manage the SASF are recovered through licence fees collected by PIRSA Fisheries and Aquaculture.

The Total Allowable Commercial Catch (TACC) was set at 1,000 t in 1992 (calendar year) and increased to 3,500 t during 1993–1997 (Figure 1–1). In 1998, the TACC was set at 12,500 t, but was reduced to 3,500 t after the mass mortality event in late 1998 and to 3,800 t in 1999 and 2000. The stock recovered rapidly, and the TACC increased to 51,100 t in 2005. From 2007 to 2017, the TACC increased from 30,000 t to 42,750 t. The TACC was 42,750 t from 2017 to 2021. The TACC increased to 45,000 t in 2022 and to 50,000 t in 2023–2025. From 2010, onwards, there has been a cap on the catch taken from Spencer Gulf (Figures 1–1 and 1–2). In 2022, under-catch and over-catch quota arrangements were implemented in the SASF, where, if under-catch occurred, up to 10% of total quota entitlements on a licence could be carried over into the subsequent fishing season (PIRSA 2021).

From 2014 to 2019, the SASF was divided into two main zones: Gulfs Zone (Spencer Gulf and Gulf St Vincent) and Outside Zone (Figure 1–2). From 2020 to 2022, the Gulfs Zone was temporarily split into two zones: the Spencer Gulf (SG) Zone and Gulf St Vincent (GSV) Zone at the longitude 137°10'E, (PIRSA 2020; Figure 1–2). The management arrangement for the SG Zone remained the same as for the previous Gulfs Zone but up to 6,000 t from the Outside Zone could be taken from the GSV Zone (PIRSA 2020). In 2023, the spatial management arrangement of three zones (SG Zone, GSV Zone, Outside Zone) was described in the current Management Plan (PIRSA 2023) and were permanently implemented through in the *Fisheries Management (Sardine Fishery) Regulations 2021* in 2025.

The TACC of 50,000 t in 2024 included up to 30,000 t from the SG Zone and 20,000 t from the Outside Zone, of which a maximum of 6,000 t could come from the GSV Zone. These arrangements remained in place in 2025 (Figures 1–1 and 1–2; Table 1–2).

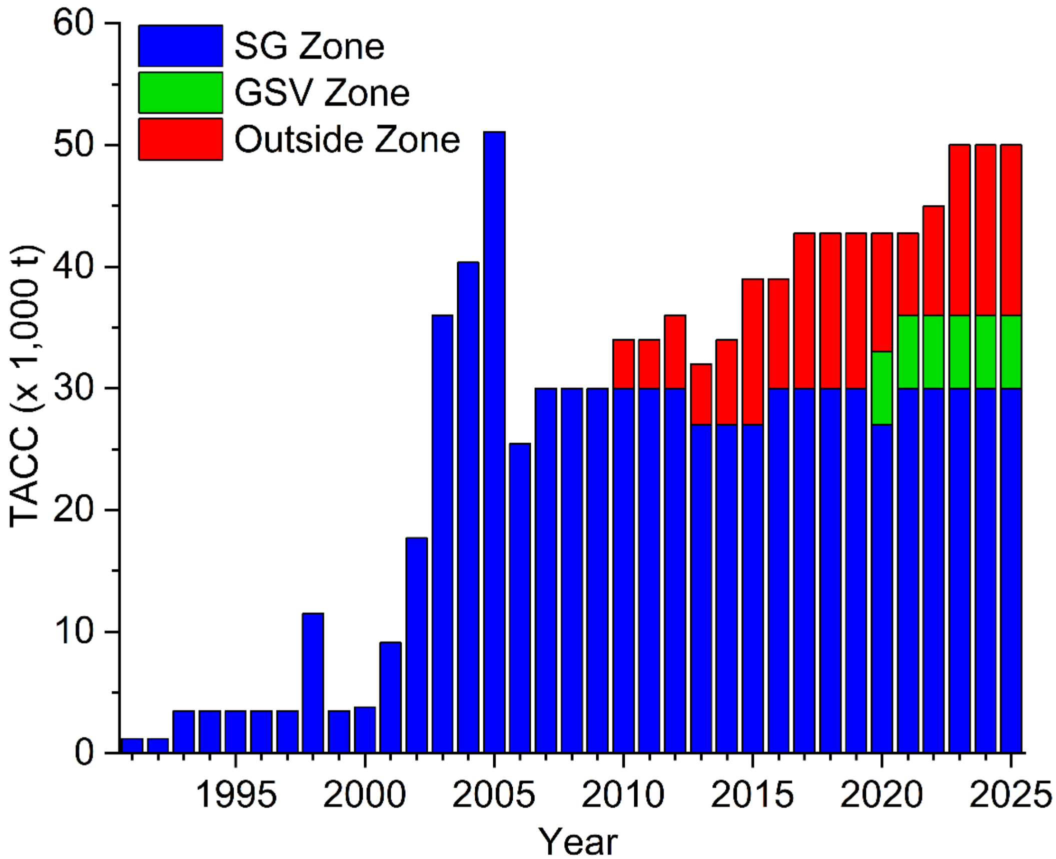


**Figure 1-1.** Total Allowable Commercial Catch (TACC) for the South Australian Sardine Fishery (SASF) between 1991 and 2025 for Spencer Gulf (SG) Zone, Outside Zone, and Gulf St Vincent (GSV) Zone (see Figure 1–2).

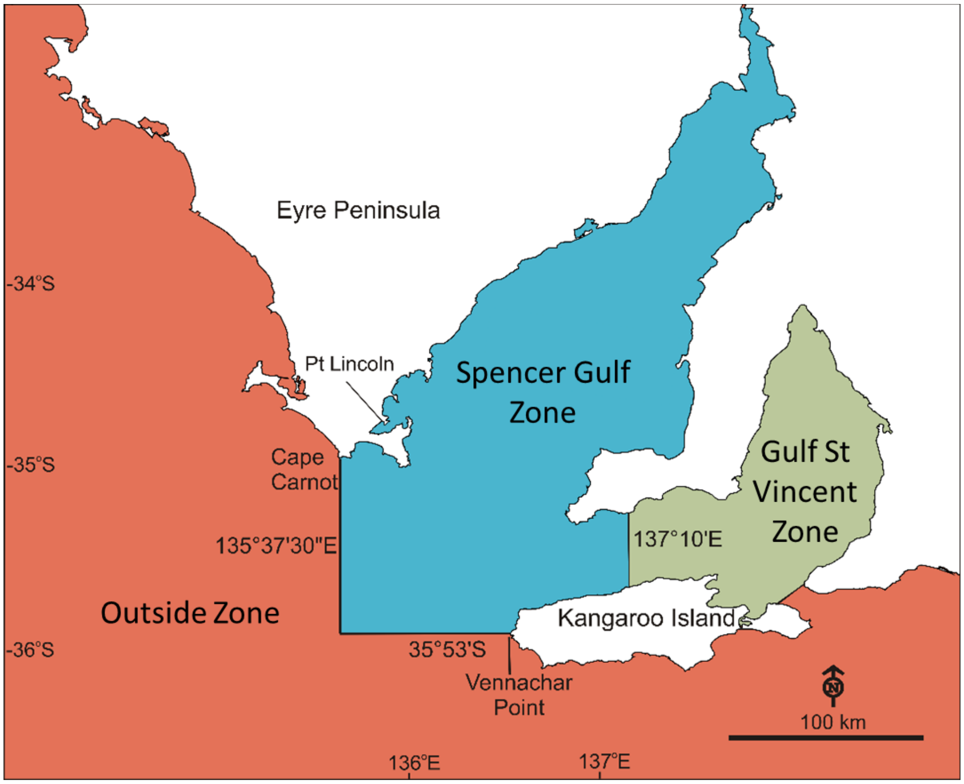


**Figure 1-2**. The three spatial management zones defined in the Harvest Strategy for the SASF (source PIRSA 2023).

Since 1998, the key biological performance indicator for the SASF has been the estimate of spawning biomass obtained using the DEPM. From 1997 to 2006, the TACC for the following calendar year was set as a proportion of the spawning biomass (i.e. 10.0–17.5%, depending on the size of the spawning biomass). From 2007 to 2009, the indicative TACC was set at 30,000 t (PIRSA 2007), while the estimate of spawning biomass remained between 150,000 and 300,000 t. In 2014 (revised in 2023), a tiered Harvest Strategy (Figure 1–3) was established that sets the TACC based on the size of the spawning biomass and level of monitoring and assessment (Table 1–1). At Tier 3, DEPM and stock assessments are done in alternate years, and the maximum TACC is 45,000 t. At Tier 1, the maximum TACC is 55,000 t, and DEPM and stock assessments are both undertaken annually. At Tier 2, the maximum TACC is 50,000 t, and the DEPM is undertaken annually with a stock assessment done biennially. At all Tiers, an ecosystem assessment is required every four years and would replace a stock assessment in that year if both were set to occur at the same time (PIRSA 2023). Lower TACCs are set at each Tier if the spawning biomass is below 200,000 t. The SASF was managed at Tier 3 in 2015, 2016 and 2022, and at Tier 2 from 2017 to 2021, and from 2023 to 2025.

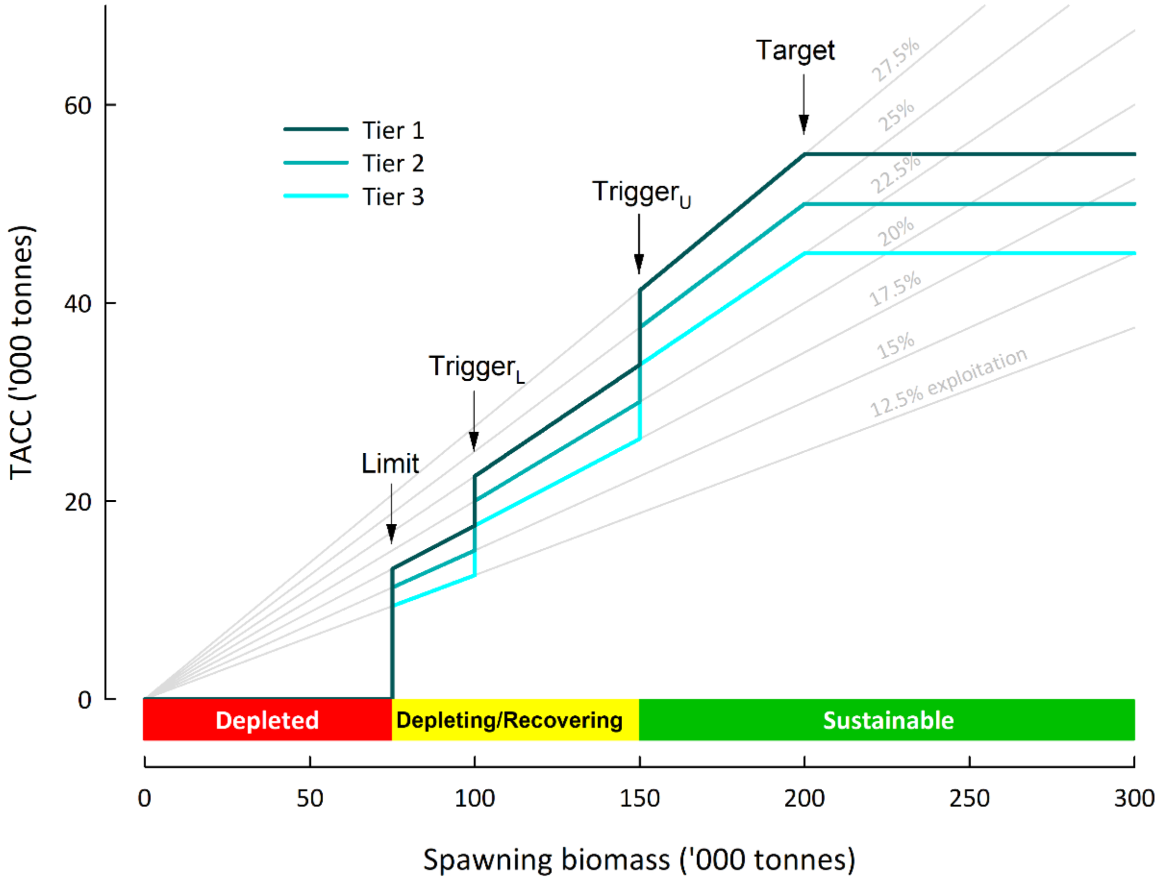


**Figure 1-3**. The relationship between spawning biomass, stock status and level of exploitation (or TACC) of the Sardine Harvest Strategy for each Tier. Reference Range: Limit (75,000 t), $Trigger_L$ (lower; 100,000 t), $Trigger_U$ (upper; 150,000 t), Target (200,000 t). Source: PIRSA 2023.

**Table 1-1**. Decision making rules for the tiered Harvest Strategy. Abbreviations: *SpB*: spawning biomass; $B^0$: initial biomass; TACC: total allowable commercial catch; ER: exploitation rate. Source: PIRSA 2023.

| *Reference Range* | *SpB (t)* | *% $B^0$* | *Tier 1* | | *Tier 2* | | *Tier 3* | |
|---|---|---|---|---|---|---|---|---|
| | | | *TACC (t)* | *Max ER* | *TACC (t)* | *Max ER* | *TACC (t)* | *Max ER* |
| *Upper Target* | *≥200,000* | *>67%* | *55,000* | *27.5%* | *50,000* | *25%* | *45,000* | *22.5%* |
| *Lower Target* | *<200,000 to ≥150,000* | *50-67%* | *41,250-55,000* | *27.5%* | *37,500-50,000* | *25%* | *33,750-45,000* | *22.5%* |
| *Upper Trigger* | *<150,000 to ≥100,000* | *33-50%* | *22,500-33,750* | *22.5%* | *20,000-30,000* | *20%* | *17,500-26,250* | *17.5%* |
| *Lower Trigger* | *<100,000 to ≥75,000* | *25-33%* | *13,125-17,500* | *17.5%* | *11,250-15,000* | *15%* | *9,375 – 12,500* | *12.5%* |
| *Limit* | *<75,000* | *<25%* | *0* | *0* | *0* | *0* | *0* | *0* |

Spatial management was established in the SASF in 2010, formalised in 2014 (two Zones: Gulfs and Outside; PIRSA 2014), and revised in 2023 (three Zones; Figure 1–2; PIRSA 2023). Since 2020, the spatial management arrangements for the SASF have been based on three Zones (PIRSA 2020, 2023). The catch that can be taken from the SG Zone and GSV Zone is determined from the mean size (mm Fork Length, FL) of Sardine taken in catches from that zone in the previous year (Table 1–2; Figure 1–2).

**Table 1-2.** Catch allocation decision table for the harvest strategy of the SASF to guide the maximum TACC allowed from the Spencer Gulf Zone (SGZ) and Gulf St Vincent Zone (GSVZ) (PIRSA 2023).

| Mean size of Sardines (MSS, mm Fork Length) | Maximum catch limits | |
|---|---|---|
| | SGZ | GSVZ |
| >142 mm | 30,000 t | 6,000 t |
| >135 mm to ≤142 mm | 27,000 t | 4,000 t |
| ≤135 mm | 24,000 t | 2,000 t |

## 1.5 Stock status classification

A national stock status classification system, Status of Australian Fish Stocks (SAFS), has been developed to assess key Australian fish stocks (Table 1-3; Roelofs et al. 2024). The classification system combines information on current stock size and the level of fishing pressure to assess 'stock status' (Roelofs et al. 2024). Each stock is classified as: 'sustainable', 'depleting', 'recovering', 'depleted', 'undefined' or 'negligible' as outlined in Table 1–3. The SASF targets the Southern Australian stock, which occurs off South Australia and eastern Western Australian (Izzo et al. 2017, Sexton et al. 2019, Ward et al. 2023). The Southern Australian stock was assessed as being sustainable in the most recent Status of Key Australian Fish Stocks (Roelofs et al. 2024).

**Table 1-3.** Stock status terminology (Roelofs et al. 2024).

| | Stock status | Description | Potential implications for management of the stock |
|---|---|---|---|
| | Sustainable | Stock for which biomass (or biomass proxy) is at a level sufficient to ensure that, on average, future levels of recruitment are adequate (*i.e.* recruitment is not impaired) and for which fishing mortality (or proxy) is adequately controlled to avoid the stock becoming recruitment impaired | Appropriate management is in place |
| | Depleting | Biomass (or proxy) is not yet depleted and recruitment is not yet impaired, but fishing mortality (or proxy) is too high (overfishing is occurring) and moving the stock in the direction of becoming recruitment impaired | Management is needed to reduce fishing pressure and ensure that the biomass does not become depleted |
| | Recovering | Biomass (or proxy) is depleted and recruitment is impaired, but management measures are in place to promote stock recovery, and recovery is occurring | Appropriate management is in place, and there is evidence that the biomass is recovering |
| | Depleted | Biomass (or proxy) has been reduced through catch and/or non-fishing effects, such that recruitment is impaired. Current management is not adequate to recover the stock, or adequate management measures have been put in place but have not yet resulted in measurable improvements | Management is needed to recover this stock; if adequate management measures are already in place, more time may be required for them to take effect |
| | Undefined | Not enough information exists to determine stock status | Data required to assess stock status are needed |
| | Negligible | Catches are so low as to be considered negligible and inadequate information exists to determine stock status | Assessment will not be conducted unless catches and information increase |

# 2. FISHERY INFORMATION

## 2.1 Introduction

This chapter presents catch, effort, size composition data and catch-per-unit-effort (CPUE) for the SASF from 1 January 1991 to 31 December 2024. This information is used to describe the main spatial and temporal patterns in the fishery and provides key inputs to the stock assessment model (Chapter 5).

## 2.2 Methods

### 2.2.1 Data collection

Catch and effort data were collated from commercial fishing logbooks. Prior to 2001, catch and effort were reported according to the statistical reporting blocks comprising South Australian Marine Fishing Areas (MFAs). Following the implementation of SASF logbooks in 1998, catch and effort were reported by latitude and longitude for each purse-seine net-set. Estimated catches presented by month and year were aggregated from daily catches recorded in logbooks. CPUE estimates were based on these aggregated catches and corresponding effort data. Actual total annual catches were determined from the Catch Disposal Records (CDRs) collated from landings reported by PIRSA Fisheries and Aquaculture. Minor changes to historical catch and effort values presented in this report reflect revised spatial data handling to match logbook data are with catch sampling data.

### 2.2.2 Commercial catch sampling

Between 1995 and 2024, commercial catch samples were collected under a range of sampling protocols; since 2008, independent observers present on about 10% of fishing trips have taken a sample of around 30 fish from each observed net-set. The observer program ceased in April 2020 due to the COVID-19 lockdown; the program resumed in 2021. Therefore, few catch samples were collected for the 2020 season. In 2019, only length and otolith data were collected due to a freezer breakdown preventing other morphometric data from being taken.

Size frequencies were constructed from caudal fork lengths (FL) aggregated into 10 mm length classes for all samples. The age determination method is described in Chapter 3. Catch weightings were applied to size and age frequency data collected since 2010. Prior to 2010, not all catch samples could be be linked to the corresponding net-sets. Length and age-frequencies were weighted by the total amount of catch taken in the corresponding net-set. Applying catch weightings (since 2010) has resulted in slight adjustments to the mean size of Sardine over this period, which are more representative of the mean size of fish caught by the SASF compared to previous reports.

Sex ratio was calculated as the proportion of female Sardines in commercial catch samples. Sex was not recorded for commercial samples obtained in 2007.

Kernel density distributions were used to plot the spatial trends in the mean size of Sardine (mm FL) in commercial catch samples from 2010 to 2024 to meet requirements of data confidentiality (≥ 5 licences reporting catch). Data were plotted as a 2D kernel density estimation ('ked2d' function using MASS R package; Venables and Ripley 2002) on spatial locations grouped by categories of fish length: ≤135; 135-142; 142-155; >155 mm FL. Density estimation makes inferences about the underlying probability density function everywhere, including where no data are observed. Aggregating the individually smoothed contributions gives an overall picture of the structure of the data and its density function, while obscuring the identity and locale of individual data points.

## 2.3 Results

### 2.3.1 Effort, catch and CPUE

*Annual patterns*

The SASF expanded quickly after its inception in 1991, with total effort increasing from 5 boat-nights in 1991 to 736 boat-nights in 1994 (Figure 2-1). Effort was reduced in 1995 following the first mass-mortality event (Ward et al. 2001b) but increased again to 530 boat-nights in 1998. In 1999, after the second mass-mortality event, effort declined to 360 boat-nights. Since then, the fishery expanded rapidly, with effort reaching 1,274 net-sets across 1,232 boat-nights in 2005, before dropping to 840 net-sets and 710 boat-nights in 2006. Between 2007 and 2021, effort remained relatively stable at ~760–1100 net-sets over ~630–900 boat-nights. In 2024, effort was 936 net-sets over 646 boat-nights (Figure 2-1).

Total catch increased from 7 t in 1991 to ~3,000 t in 1994 (Figure 2-1). Following the first mass-mortality event, catch declined but then rose to ~6,000 t in 1998. After the second mortality event, catch fell again to ~3,000 t in 1999. The fishery then expanded substantially, with estimated catches reaching ~40,000 t in 2005 and ~24,000 t in 2006. Between 2007 and 2021, estimated catches ranged from 27,500 to 40,600 t. Estimated catch increased to ~44,000 t in 2022, was ~41,500 t in 2023, and reached ~45,000 t in 2024 (Figure 2-1).

Total annual catches recorded in CDRs exceeded catches estimated in logbooks in most years but showed similar trends. Catches from CDRs increased from 2,597 t in 1995 to 42,475 t in 2005, then fell to 25,137 t in 2006 (Figure 2–1). From 2007 to 2021, annual catches reported in CDRs ranged between 29,854 t in 2009 to 42,511 t in 2017. The catch increased to 47,354 t in 2022, declined to 45,554 t in 2023, then increased to 48,502 t in 2024.

Mean annual $CPUE_{boat\text{-}night}$ progressively increased from 1 $t.boat\text{-}night^{-1}$ in 1991 to an historical peak of 70 $t.boat\text{-}night^{-1}$ in 2024 (Figure 2–1). From 1999 to 2004, mean $CPUE_{boat\text{-}night}$ rose rapidly from 9 $t.boat\text{-}night^{-1}$ to 36 $t.boat\text{-}night^{-1}$. It then continued to increase, reaching 57 $t.boat\text{-}night^{-1}$ in 2018, stabilising at 60 $t.boat\text{-}night^{-1}$ in 2022 and 2023, before rising to 70 $t.boat\text{-}night^{-1}$ in 2024.

Mean annual $CPUE_{net\text{-}set}$ increased from 7.2 $t.net\text{-}set^{-1}$ in 2000 to 32.4 $t.net\text{-}set^{-1}$ in 2004, remained between 28.2 and 33.5 $t.net\text{-}set^{-1}$ until 2012, then increased to 40.1 $t.net\text{-}set^{-1}$ in 2013 (Figure 2–1). From 2014 to 2023, it ranged between 36.9 and 44.4 $t.net\text{-}set^{-1}$, before increasing to 48.4 $t.net\text{-}set^{-1}$ in 2024.

*Intra-annual patterns*

The intra-annual pattern in fishing effort has been reasonably consistent over the last 20 years with relatively little fishing occurring from July to October and effort and catches typically increasing during November–December (Figure 2–2). Catches continued to increase during January–February and usually peaked in March–April. The peak fishing season reflects the generally calm weather between April and June and the high demand for tuna feed during this period. The months where large catches have been taken from the Outside, SG, and GSV Zones have varied among years (Figure 2–2).

*Spatial patterns*

From 1991 until the second mortality event in 1998, most Sardine were taken from Spencer Gulf (Figure 2–3). From 1999 onwards, a small proportion of the catch has usually been taken from the Outside Zone, mainly off Coffin Bay (Figures 2–3; 2–4a, b). In 2002 and 2003, the fishery expanded northwards in Spencer Gulf (Figure 2–4a). From 2003 to 2012, significant catches were also taken from Investigator Strait in most years. Since 2010, when additional quota was allocated outside Spencer Gulf, an increasing proportion of the total catch has been taken from the eastern Great Australian Bight.

More than 6,500 t were taken from the Outside Zone each year since 2014 (Figure 2–3). In 2017, the TACC from the Outside Zone had increased to 12,750 t and catches increased accordingly. Substantial catches have been taken southeast of Kangaroo Island since 2017 (Figure 2–4b). In 2020, 6,000 t of TACC from the Outside Zone was allocated to the temporary GSV Zone, which was subsequently incorporated into the current Management Plan (PIRSA 2023), and the total Outside zone TACC was increased to 15,000 t. The total Outside Zone TACC was further raised to 20,000 t in 2023. The catch taken from Gulf St Vincent has been relatively small (i.e. <1,000 t in most years) but has increased considerably since 2020 (Figure 2–4b), reaching ~5,500 t in 2020, and was 5,000–5,700 t between 2022 and 2024.

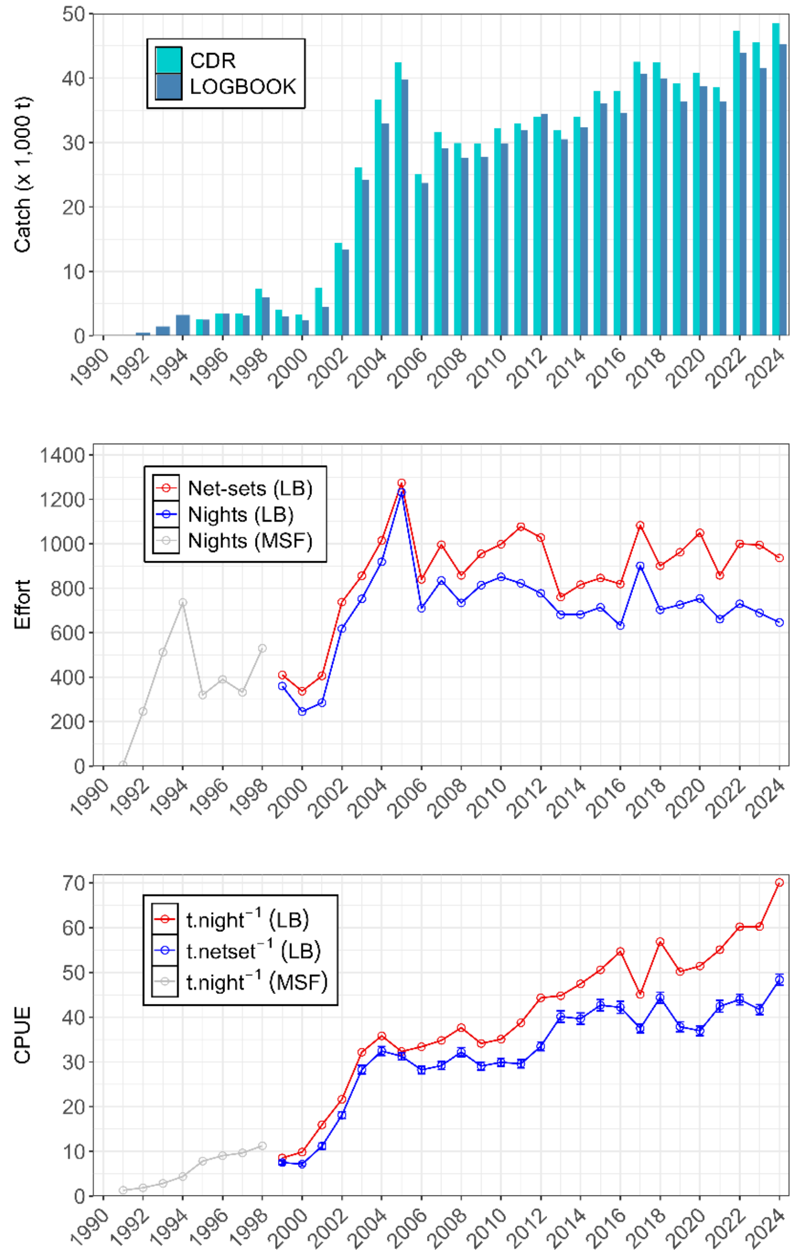


**Figure 2-1.** Total catches (estimated from logbooks, CDR), fishing effort (nights, net-sets) and mean annual CPUE (t.night$^{-1}$, t.net-set$^{-1}$, ± SE). Data prior to 1999 is derived from Marine Scalefish Fishery (MSF) records. Specific SASF logbooks (LB) were introduced in 1999.

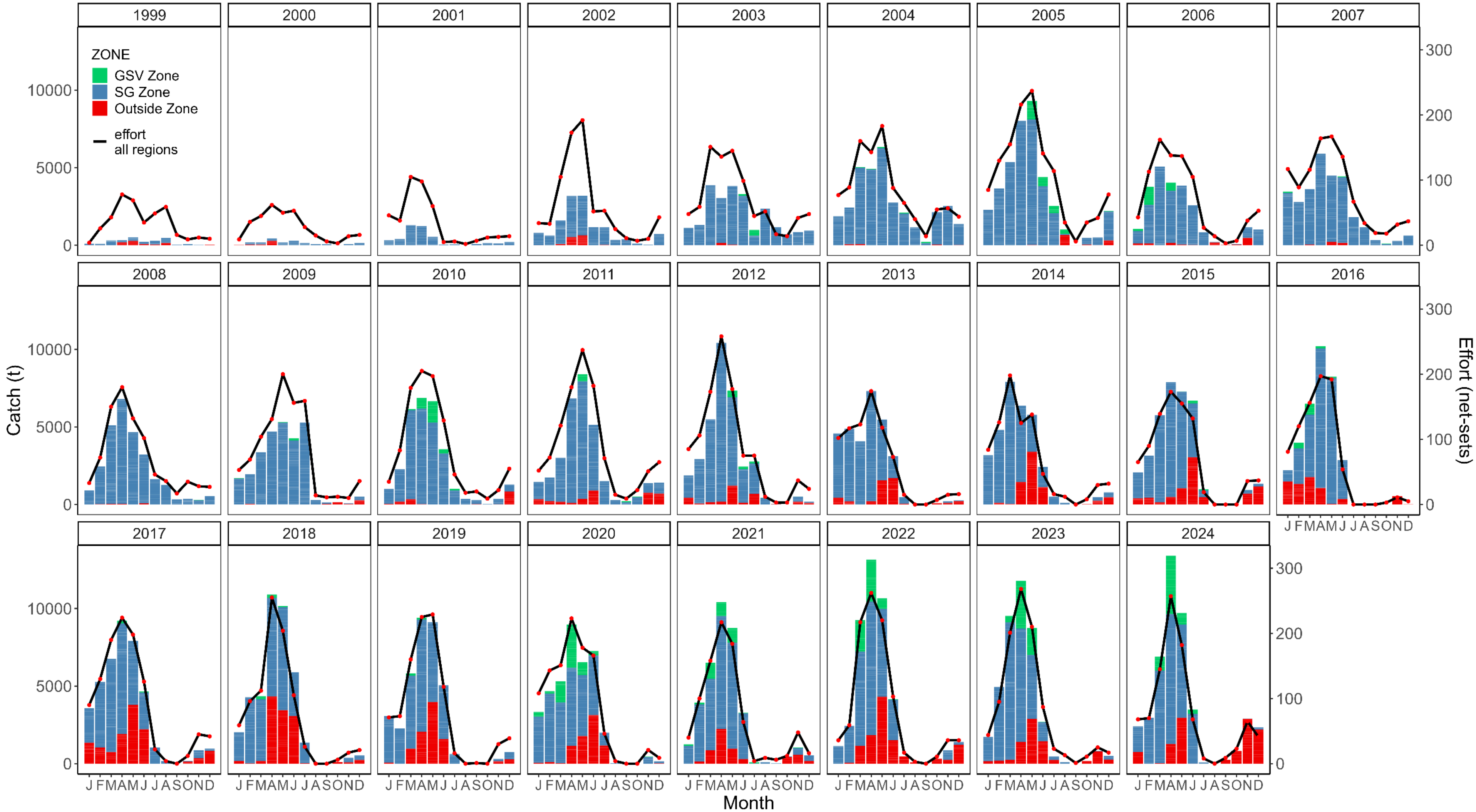


**Figure 2-2.** Intra-annual patterns in Sardine catch (tonnes, bars) by region and effort (net-sets, red points with black lines, all regions) in SASF between 1999 and 2024. Zones: GSV: Gulf St Vincent; SG: Spencer Gulf.

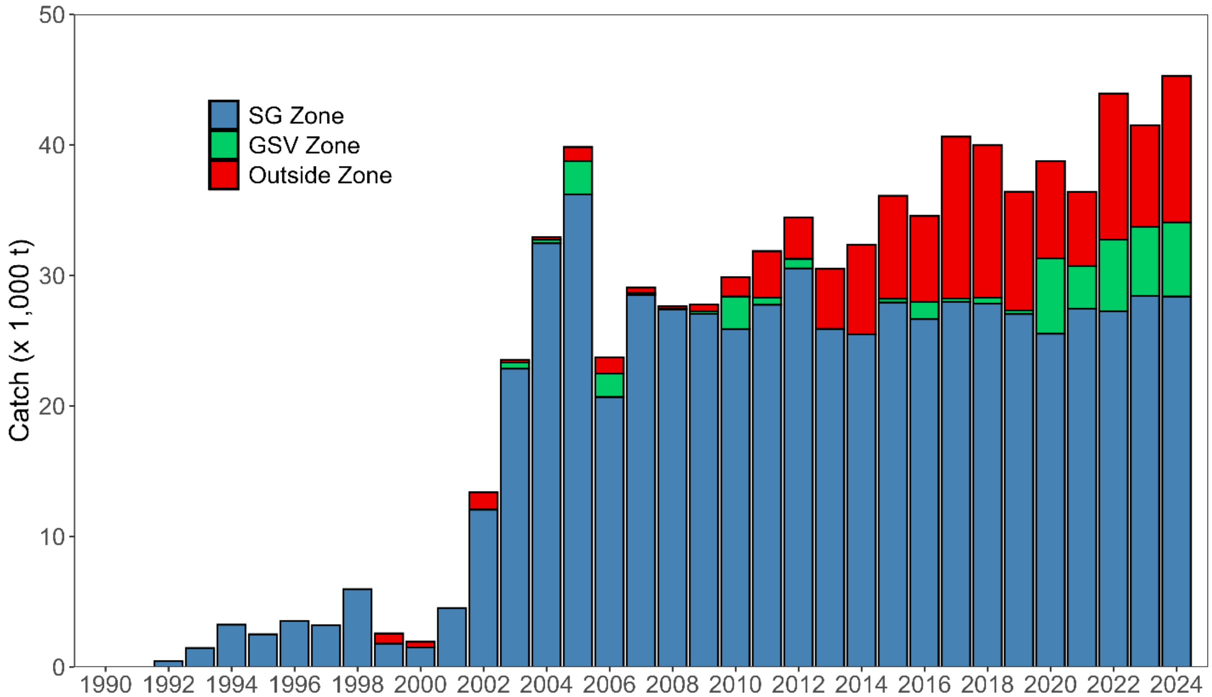


**Figure 2-3.** Annual Sardine catch (tonnes, logbook data) by zone between 1992 and 2024. Zones: GSV: Gulf St Vincent; SG: Spencer Gulf.

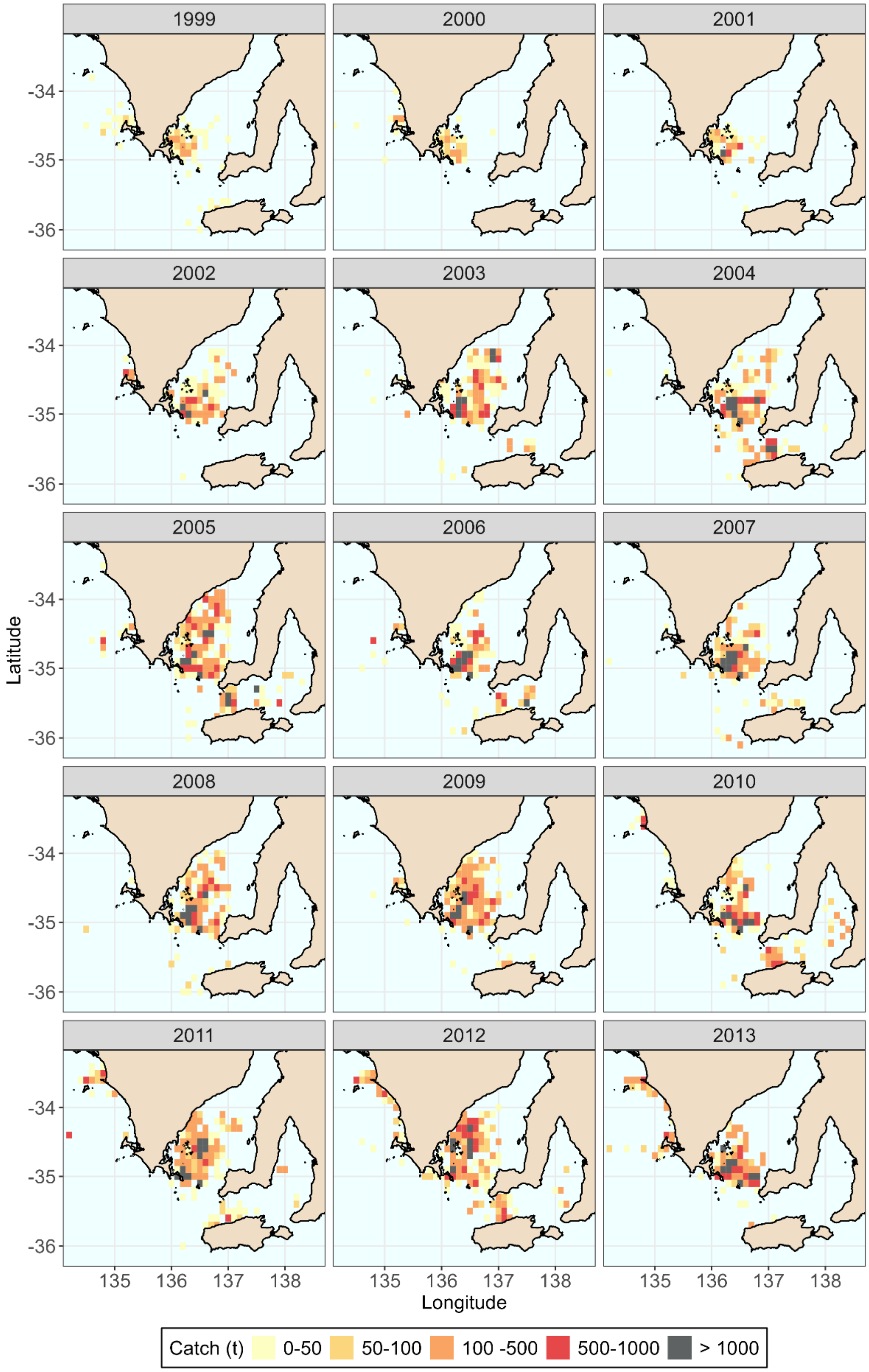


**Figure 2-4a**. Spatial trends in Sardine catches (tonnes) between 1999 and 2013.

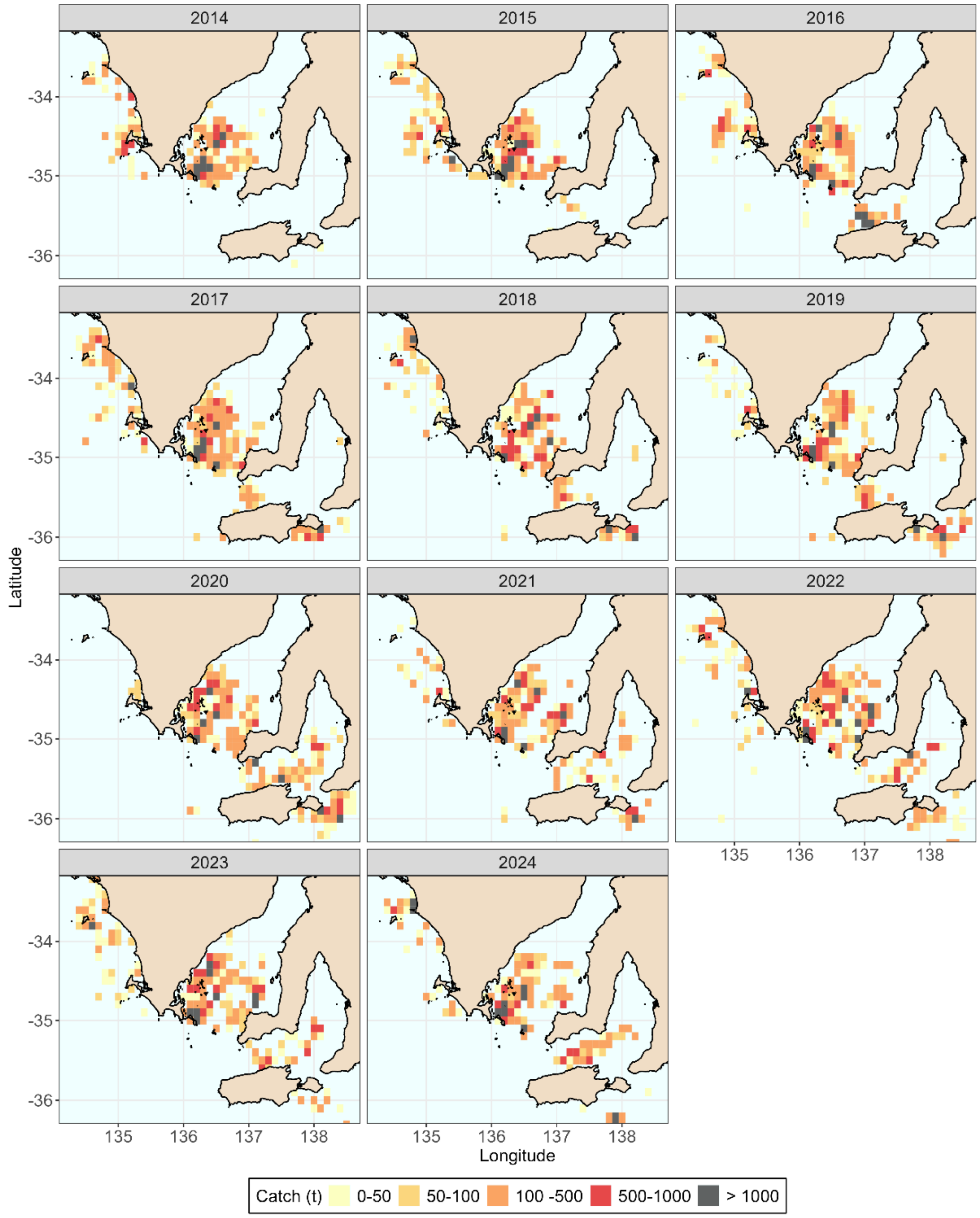


**Figure 2-4b**. Spatial trends in Sardine catches (tonnes) between 2011 and 2024.

### 2.3.2 Catch composition

*Size frequencies*

In 1995, the modal size of Sardine caught in the SG Zone was 140 mm FL with sizes mostly ranging from 130–170 mm FL (Figure 2–5). The modal size declined to 130 mm FL in 1996 and was 120 mm FL in 1998. Between 1999 and 2002, Sardine from the SG Zone were mostly ≥140 mm FL with modes between 140- and 170-mm FL. In 2003 and 2004, size structures were bimodal, with juveniles (80–120 mm FL) and adults (150–180 mm FL) present. Prior to 2003, few SG Zone samples included Sardine ≤100 mm FL. Between 2005 and 2010, size distributions remained stable with a mode at 140–150 mm FL, and a size range from 120 to190 mm FL. The modal size dropped to 130 mm in 2011 and 2012, increased to 140 mm during 2013–2016, peaked at 150 mm in 2017 and 2018, then declined to 140 mm from 2019–2021, where it remained in 2023 and 2024 (Figure 2–5).

Larger size ranges were caught in the Outside Zone throughout the history of the fishery. In the Outside Zone, Sardine of 150–180 mm FL dominated catches between 1995 and 1998 (Figure 2–6). After the second mortality event in 1999, the modal length fell to 130 mm FL but increased to sizes above 140 mm FL in 2000 and reached 170–190 mm FL in 2005 and 2006. Few samples were taken in 2007 and 2008 and none in 2009. From 2010 to 2015, the modal size remained above 140 mm FL. In 2016 and 2017, sizes ranged 90–190 mm FL. Size structures from catches taken in the Outside Zone were bimodal in 2018 (modes: 140 mm FL and 160 mm FL), with a smaller modal length of 130 mm FL in 2019. No samples from catches in the Outside Zone were collected in 2020. The size structures were bimodal in 2021 (modes: 140 mm FL and 160 mm FL), 2022 (modes: 130 mm FL and 160 mm FL), and 2023 (modes: 150 mm FL and 170 mm FL). In 2024, the modal size was 170 mm FL.

Catch samples from the GSV Zone have been available since 2009, with a modal size of 130 mm FL in 2009, 2010, 2011 and 2016 (Figure 2–7). No catch samples were available from 2013 to 2015. In 2018, the size structure was bimodal (modes: 120 mm FL and 150 mm FL), with a single mode at 160 mm FL in 2020, 130 mm FL in 2021 and 140 mm FL in 2022. In 2024, the size structure was bimodal, with modes at 130- and 160-mm FL.

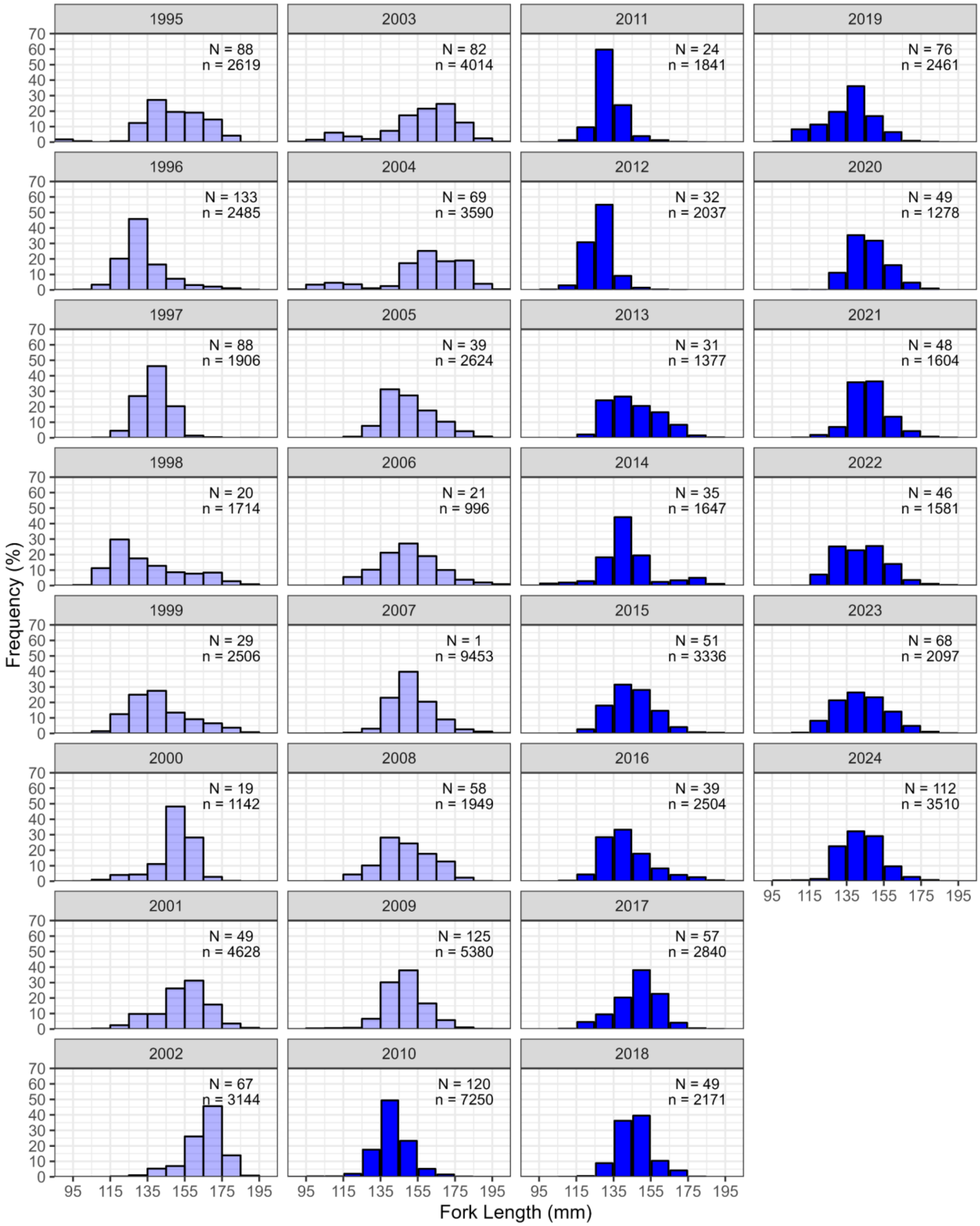


**Figure 2-5**. Length frequency distributions of Sardine measured (n) from commercial catch samples (N) for the Spencer Gulf Zone between 1995 and 2024. Dark blue: catch weighted distributions; pale blue: not catch weighted.

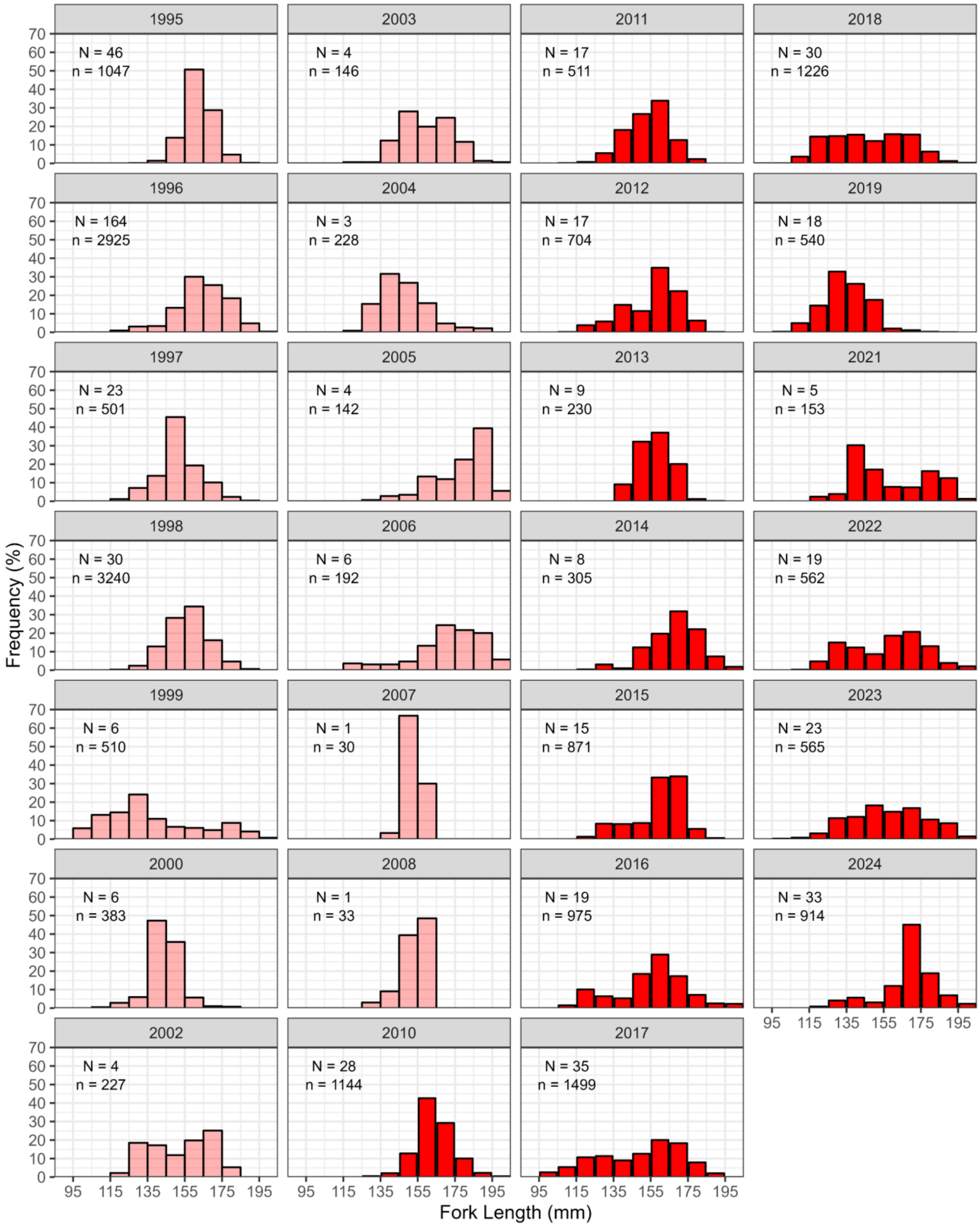


**Figure 2-6**. Length frequency distributions of Sardine measured (n) from commercial catch samples (N) for the Outside Zone between 1995 and 2024. Bright red: catch weighted distributions; pale red: not catch weighted.

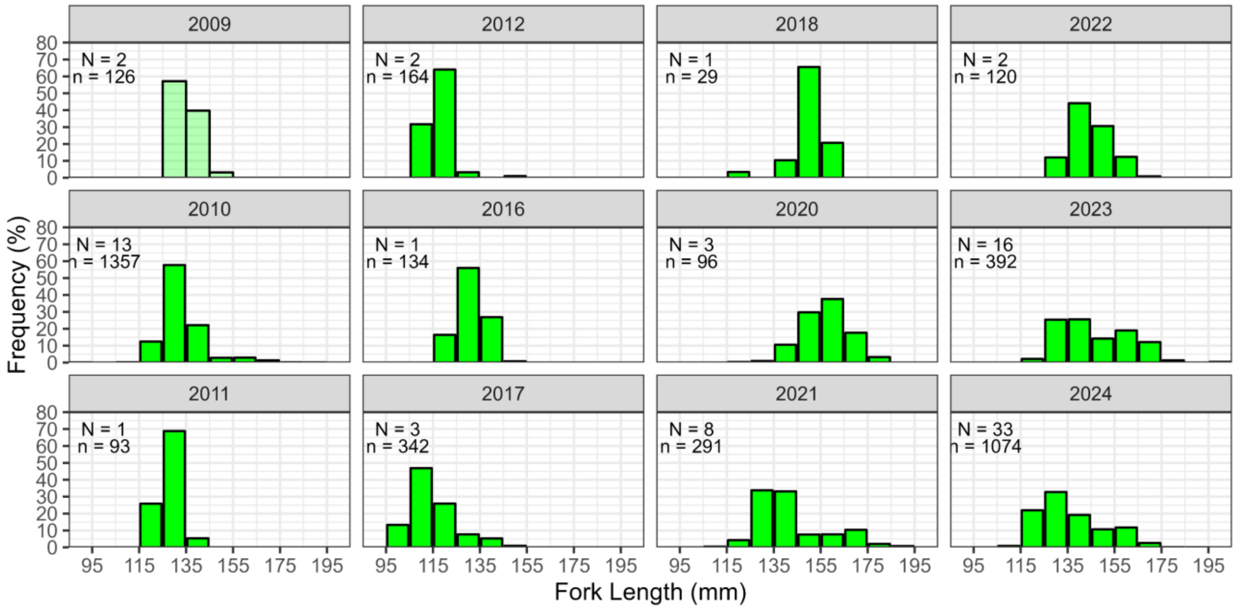


**Figure 2-7.** Length frequency distributions of Sardine measured (n) from commercial catch samples (N) for the Gulf St Vincent (GSV) Zone between 2009 and 2024. Bright green: catch weighted distributions; pale green: not catch weighted.

*Mean size*

The mean size of Sardine from Spencer Gulf (i.e. SG Zone since 2020) ranged from 133 to 149 mm FL between 1995 and 1999 and increased to 166 mm FL in 2002 (Figure 2–8). Between 2003 and 2009, mean size in Spencer Gulf was relatively stable between 149- and 159-mm FL then declined to 128 mm FL in 2012. From 2013 to 2018, mean size in Spencer Gulf remained stable with a rangefrom 143 to 148 mm FL. The mean size declined to 138 mm FL in 2019. The drop in mean size to below the reference size of 142 mm FL triggered a reduction in TACC from 30,000 t to 27,000 t for the SG Zone in 2020. In 2020 and 2021, the mean size increased to 148 mm FL. From 2022 to 2024, the average size of sardine in Spencer Gulf was stable at 144 mm FL.

The mean size of Sardine from the Outside Zone was generally higher than for Spencer Gulf (Figure 2–8). Between 2010 and 2016, the mean size was stable, ranging between 153- and 164-mm FL, but then declined progressively to 136 mm FL in 2019. The low mean size in 2019 resulted from substantial catches of small fish (<142 mm FL) taken off the south-eastern coast of Kangaroo Island (SARDI unpublished). In 2020, no samples were collected that from catches in the Outside

Zone. Between 2021 and 2023, mean Sardine size in the Outside Zone was stable at 159 mm FL, increasing to 169 mm FL in 2024.

The mean size of Sardine from Gulf St Vincent (i.e. GSV Zone since 2020) ranged from 115 to 136 mm FL from 2009 to 2017, then increased to 151 mm FL in 2018 and 157 mm FL in 2020. In 2021, 2022 and 2023 the mean size ranged from 143 mm FL to 148 mm FL, before declining to 137 mm FL in 2024, which is below the reference point for maximum catch limit in both Gulf Zones of 142 mm FL.

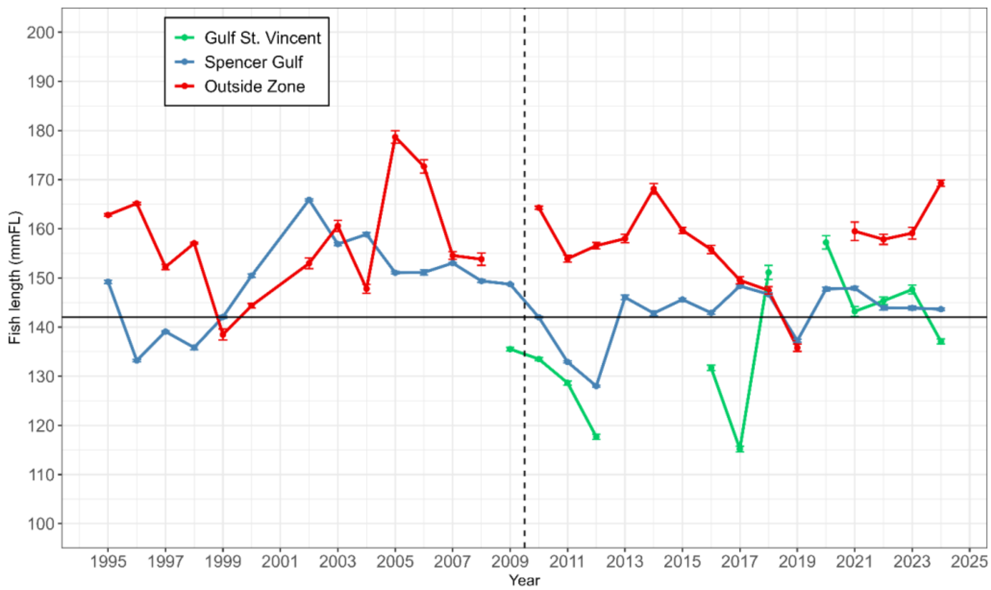


**Figure 2-8**. Average fork length (mm FL) by year for commercial samples from the three regions of the SASF: Spencer Gulf (SG Zone), Outside Zone, Gulf St Vincent (GSV Zone), error bars are standard error. Horizontal line indicates the reference point for maximum catch limit for the Gulf Zone of 142 mm FL (Table 1–2). Vertical dashed line indicated the time after which catch weighting was applied to estimates (2010–2024).

*Spatial distribution of size*

Between 2010 and 2024, Sardine >155 mm FL from catch samples mainly occurred off the western Eyre Peninsula in the Outside Zone, and in the mouth of Spencer Gulf and Investigator Strait (Figure 2–9) in the SG Zone. Sardine ≤ 135 mm FL predominantly occurred in southwestern Spencer Gulf (Figure 2–9) but also occurred off south-eastern Kangaroo Island and in central Gulf St Vincent (SARDI unpublished; confidential data not shown). Sardine between 135 to 155 mm FL were distributed across the fishing grounds but mainly occurred in the southern Spencer Gulf, Investigator Strait and southern Gulf St Vincent (Figure 2–9).

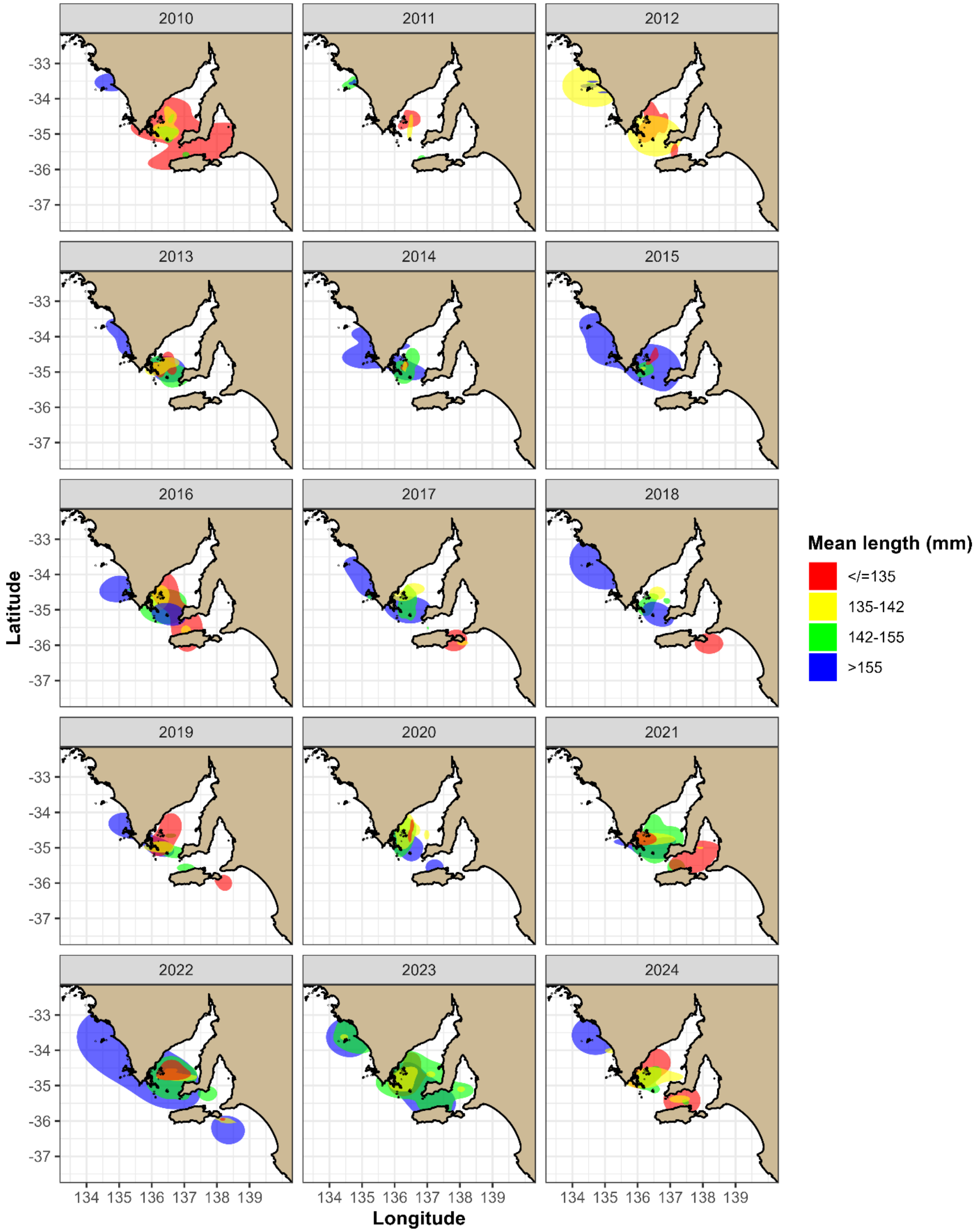


**Figure 2-9**. Kernel density distributions of the spatial trends in the mean size of Sardine (mm FL) from 2010 to 2024 in commercial catch samples. Data are plotted as kernel density distributions to meet requirements of data confidentiality (≥5 licences reporting catch).

*Sex ratio*

The annual sex ratio (by number) in commercial catches has varied over the history of the fishery. For most years, the sex ratio has been skewed towards females (Figure 2–10; Table A1). The highest proportion of females occurred in both 1995 and 2005 at 63%, while the lowest proportion of females was 47% in both 2000 and 2013 (Figure 2–10; Table A1).

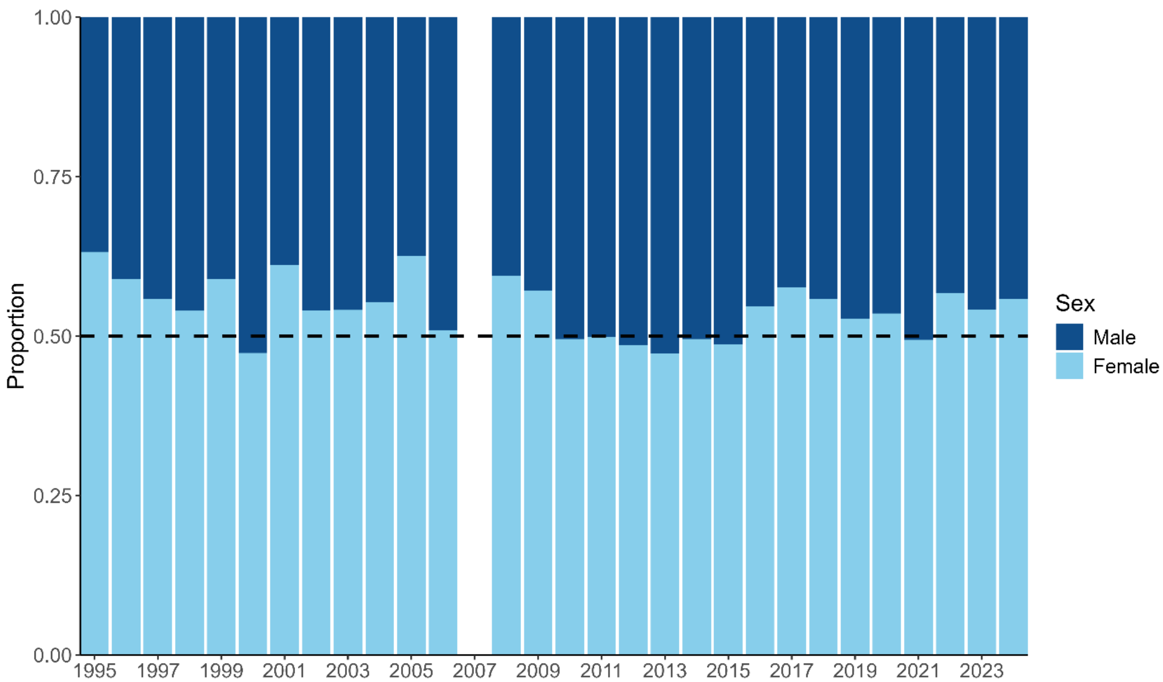


**Figure 2-10.** Sex ratio of commercial catch samples from all regions between 1995 and 2024. Data are unavailable for 2007 and limited for 2019. Dashed line represents a 1:1 sex ratio. Specific annual values are listed in Table A1.

## 2.4 Discussion

The SASF has grown rapidly since its inception. The TACC for 2017 to 2021 of 42,750 t was 40 times higher than the TACC in 1992 (1,000 t) and more than ten times higher than the TACC in 2000 (3,500 t). The TACC increased further in 2022 to 45,000 t, and to 50,000 t in 2023, 2024 and 2025. This rapid growth has occurred despite the impacts of two mass mortality events (1995 and 1998), each of which killed more fish than any other single-species mortality event recorded (Jones et al. 1997, Ward et al. 2001b).

Another notable feature of the SASF is the stability in catches in recent years. While factors such as population dynamic processes (Hilborn & Walters 2013) and stable environmental conditions (Cury et al. 2000; Checkley et al. 2009) can contribute to consistent catch levels, this stability is likely driven in large part by the precautionary harvest strategy, which was designed to account for the imprecision in estimates of spawning biomass obtained using the DEPM. Under the current harvest strategy for the SASF, the maximum TACC of 55,000 t can only be set when DEPM surveys and integrated stock assessments are done annually, and the spawning biomass is greater than the target reference point of 200,000 t. The fishery is currently positioned at Tier 2 with a maximum TACC of 50,000 t. At Tier 2, DEPM surveys are completed annually with integrated stock assessments undertaken every second year. At all Tiers, an ecosystem assessment is required every four years, and under the current harvest strategy, is set to be delivered in 2026 (PIRSA 2023).

Fishing effort of the SASF is concentrated in a small proportion of the total area where the managed population is distributed. Since 2010, a range of management arrangements were implemented to limit the catch from the SG and GSV Zones (particularly Spencer Gulf), reduce the capture of small fish from those Zones, and increase the catch from the Outside Zone. This approach established explicit rules to limit the total catch that can be taken from the Gulfs Zone (SG + GSV) based on the mean size of fish taken from that Zone in the previous year. In 2020, a third zone was implemented that separated the Gulfs Zones into the SG Zone and the GSV Zone (PIRSA 2020). These management approaches have been successful in increasing the mean size of fish taken from the Gulf Zones and shifting effort and catch across the region. The spatial management arrangements of three zones (trialled since 2020) have been permanently applied in the current Management Plan (PIRSA 2023) and in the *Fisheries Management (Sardine Fishery) Regulations 2021* in 2025. The percentages of the catch taken in the Outside Zone and the GSV Zone have increased substantially since 2010. The maximum catch recorded in logbooks from the Outside Zone was 12,400 t in 2017, which represented 31% of the total catch that year.

Prior to 2020, relatively little catch was taken from the GSV Zone. In 2024, the Sardine fishery reached its highest recorded catch of 48,502 t (CDR, total Logbook catch estimate 45,277 t), with 62.7% taken from the SG Zone, 24.7% from the Outside Zone, and 12.7% from the GSV Zone (Logbook data).

Changes in management arrangements and fishing patterns over the history of the SASF have influenced the size composition of fish taken in catches. Size-based decision rules implemented in 2010 have resulted in fishers targeting larger fish in both Gulf zones, i.e. >142 mm FL. However, in 2019, the mean size of fish taken from the combined Gulfs zones (SG + GSV) dropped to below the reference size of 142 mm FL and caused a reduction in TACC in 2020 from 30,000 t to 27,000 t for the SG Zone. Catches in 2024 from the Outside Zone contained larger fish than catches from SG and GSV Zones. The mean size of Sardine in GSV declined to 137 mm FL in 2024, which is below the 142 mm FL reference point for both Gulf Zones. A spatial pattern of the size-based distribution of Sardine off South Australia, based on size composition data from commercial catches, is beginning to emerge. Further understanding of the size-based distribution of Sardine in South Australian waters would be useful, given that size selectivity in the SASF has likely changed over time.

The increase in CPUE over the history of the SASF reflects increased catch capacity of the fleet. The reduction in CPUE in 2017 was interpreted by fishers to reflect a change in schooling behaviour of Sardine during that year. CPUE also declined in 2019, 2020 and 2023 before reaching a historical high in 2024. The results of the DEPM survey for 2017, 2019, 2020 and 2023 did not suggest that the population had declined in those years. A divergence of $CPUE_{night}$ (small increase) and $CPUE_{net\text{-}set}$ (small decrease) since 2020 may warrant further investigation in light of the changing spatial nature of the fishery, in particular the increased fishing in the GSV Zone. These results reaffirm the unsuitability of CPUE for monitoring the abundance of pelagic fishes taken in a purse-seine fishery. CPUE is not used as an index of abundance in the population modelling undertaken in Chapter 5.

# 3. AGE COMPOSITION AND REPRODUCTIVE BIOLOGY

## 3.1 Introduction

Age determination studies of Sardine have involved counting growth increments in scales (Blackburn 1950) and sagittal otoliths (ear bones) (Butler et al. 1996, Fletcher and Blight 1996), and modelling the formation of marginal increments in otoliths (Kerstan 2000). Daily deposition of growth increments in the otoliths of larvae and juveniles has been validated in laboratory trials (Hayashi et al. 1989). Age validation studies involving the capture and maintenance of Sardine and other clupeoids have been problematic owing to logistical difficulties (Fletcher 1995) and sensitivity to handling (Rogers et al. 2003). Other methodological approaches have been used to show that translucent zones form annually in the sagittal otolith of 1+ year old Sardine off South Africa (Waldron 1998), ≤2+ year olds off North America (Barnes and Foreman 1994) and ≥4+ year olds off Western Australia (Fletcher and Blight 1996). Despite this theoretical basis for using increment-based age-determination methods, the application of these standard approaches has been problematic in Western Australia, South Australia and California due to difficulties associated with interpreting and counting opaque and translucent zones (Butler et al. 1996, Fletcher and Blight 1996, Rogers and Ward 2007).

Studies of growth dynamics of Sardine in the Benguela and California Current systems suggest that growth rates of larvae (up to 0.85 $mm.day^{-1}$) and juveniles (0.48–0.63 $mm.day^{-1}$) are high (Butler et al. 1996, Quinonez-Velazquez et al. 2000). In South Africa, Sardine were found to reach larger asymptotic sizes ($L_\infty$ = 221 mm) and have lower growth constants ($k = 1.09$ $year^{-1}$) than those off southern California ($L_\infty$ = 205 mm, $k = 1.19$ $year^{-1}$) (Thomas 1984, Butler et al. 1996). Parameter estimates for Sardine in Western Australia (Fletcher and Blight 1996) suggest that growth in this area is slower, and that fish reach smaller asymptotic sizes than those in the more productive eastern boundary current systems.

A detailed study by Rogers and Ward (2007) showed that the growth rates of Sardine are higher in South Australian waters than off other parts of the Australian coastline, but lower than those in more productive boundary current ecosystems (Ward et al. 2006). A notable finding of the study was that fish in commercial catches were younger (and smaller) than those obtained in fishery-independent samples. This finding has implications for the use of age structured models (based on fishery samples) for stock assessment of the SASF (see Chapter 5).

This chapter describes the methods used to determine age compositions from the commercial catch of Sardine in South Australian waters. Catch-at-age information presented in this chapter is a key input to the population model presented in Chapter 5.

## 3.2 Methods

### 3.2.1 Age-determination

*Otolith preparation and interpretation*

Sagittal otoliths were collected from sub-samples (n = 10–20) of the commercial catch samples and fishery-independent samples (Chapter 2). Otoliths were cleaned of excess tissue, rinsed in distilled water and dried in IWAKI™ plastic microplates. Translucent zone counts were made for one whole otolith from each fish under reflected light, immersed in water against a flat black background (Butler et al. 1996).

*Readability index*

Sardine otoliths were classified as 1 = excellent, 2 = good, 3 = average, 4 = poor and 5 = unreadable based on standard criteria relating to their interpretability (see Rogers and Ward 2007).

*Decimal age estimates from annuli counts*

To estimate decimal age for adults with a translucent zone count of one or more, an arbitrary birthdate of March 1 was assigned, which represents the time of peak spawning. The midpoint of translucent zone formation was assumed to be mid-winter (Rogers and Ward 2007). Decimal age *A* was calculated as:

$$A = \begin{cases} (\alpha - \beta_p)/365 + TZC + 0.334 & \alpha \leq \beta_s \\ (\alpha - \beta_s)/365 + TZC + 0.334 & \alpha > \beta_s, \end{cases}$$

where $\alpha$ is the date of capture, $\beta_s$ is the assumed translucent zone formation date from the same year as $\alpha$, $\beta_p$ is the assumed translucent zone formation date from the previous year, $TZC$ is the translucent zone count and 0.334 (4 decimal months) adjusts for the difference between the assigned birth-date and the approximate timing of the first translucent zone.

*Age estimations from otolith weight*

The relationship between age and otolith weight was determined using a linear model fitted to decimal age and otolith weight data from those otoliths with readability index scores of 1 and 2. Aged otoliths from commercial catch samples between 1995 and 2024 and fishery-independent samples between 1998 and 2024 were pooled for the analysis. The resulting model was used to derive an age estimate for all otoliths based on otolith weight. Due to the change in the spatial patterns of fishing over time it is not possible to separate annual effects from regional effects on the relationship (i.e. region and season were confounded), so data from all regions were used in the analysis. Otoliths collected in 2017 and 2018 were unusually opaque and were unable to be visually assigned an age. Therefore, ages were assigned to these otoliths using the linear relationship for age–otolith weight.

### 3.2.2 Size-at-maturity

Ovaries were staged macroscopically where stage 1 = immature, stage 2 = maturing, stage 3 = mature, stage 4 = hydrated (spawning) and stage 5 = spent (recently spawned). Testes were staged where stage 1 = immature, stage 2 = mature and stage 3 = mature (running ripe). Only fish sampled during the spawning season (1 December to 31 March) were included, as outside of this period stages 2 and 5 are difficult to differentiate macroscopically.

The length at which 50% of the population was mature ($L_{50}$) was estimated using a binomial generalised linear model (GLM) with a logit link function. The model was fitted separately to males and females using binary maturity assignments where immature = 0 (stage 1) and 1 = mature (stages ≥ 2). The proportion of the mature population at length $L$ calculated as:

$$P(L) = P_{max}\left(1 + e^{-\ln(19)(\frac{L-L_{50}}{L_{95}-L_{50}}}\right)^{-1}$$

where $P(L)$ is the proportion of the population mature at fork length $L$ and $P_{max}$ is the maximum proportion of mature individuals. Size-at-maturity models were fit to each sampling year to determine if $L_{50}$ has changed over the history of the fishery. Some years were omitted as insufficient data were collected within the spawning season to accurately fit the model.

A size-at-maturity ogive was produced using the data pooled across all years and fishery dependent and independent sampling. These data were also restricted to within the spawning season and the two Gulf Zones (SG and GSV).

### 3.2.3 Growth

Length-at-age was estimated using the non-seasonalised form of the von Bertalanffy growth function (VBGF) fitted to individuals that were aged with a readability index score of 1 or 2. Discrete ages were converted to decimal ages using the methods outlined previously. Preliminary analyses indicated that growth was not sex dependent and therefore the sexes were pooled. This allowed the inclusion of juvenile fish that were aged using daily ring counts and had been too young to accurately determine sex (Rogers and Ward 2007). The VBGF was represented by the equation:

$$L_t = L_\infty - (L_\infty - L_0)e^{-kt}$$

Where $L_t$ was the length at time $t$, $L_\infty$ was the asymptotic length, $k$ was the growth completion parameter ($yr^{-1}$) and $L_0$ was the length-at-age-zero. Length-at-age 95% confidence intervals were computed using 1000 bootstrap iterations.

### 3.2.4 Gonadosomatic index (GSI)

Mean monthly gonadosomatic indices (GSI) were calculated from both fishery independent and commercial samples using the equation:

$$GSI = \left[\frac{Gwt}{Fwt_{gonadfree}}\right].100$$

where *Gwt* is gonad weight and *Fwt* is gonad-free fish weight for fish with gonads of macroscopic stages ≥ 2. The mean estimate of GSI of all fish above size-at-maturity was used for both males and females to determine spawning season. It is important to note that it is sometimes difficult to macroscopically distinguish between Stage 2 and Stage 5 gonads in frozen samples.

## 3.3 Results

### 3.3.1 Age-determination

Between 1995 and 2024, a total of 25,627 otoliths from commercial and fishery-independent samples were read (Figure 3–1, Table A2). Less than 0.2% were assigned a readability index score of 1, while 6.2%, 48% and 30% were assigned scores of 2, 3 and 4, respectively. A readability index score of 5 was assigned to 16% of the otoliths (Figure 3–1, Table A2).

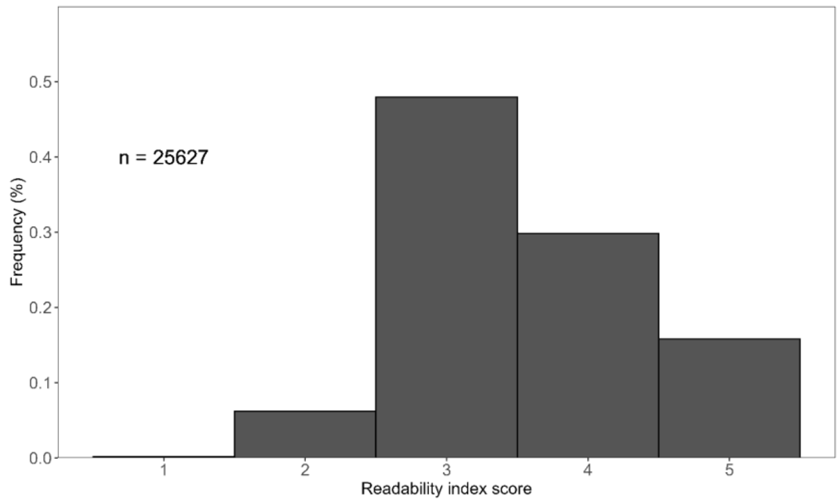


**Figure 3-1**. Readability index scores assigned to otoliths from all samples between 1995 and 2024.

*Otolith weight relationship*

The modelled relationship between decimal age (years) and otolith weight (mg) provided a reasonable fit to the data ($r^2$ = 0.819; Figure 3–2). However, while the 95% confidence intervals for the linear regression fit were narrow, the variation around the linear relationship was large. Therefore, while age can be inferred from otolith weight, the lack of precision resulting from this method means that these age estimates must be used with caution.

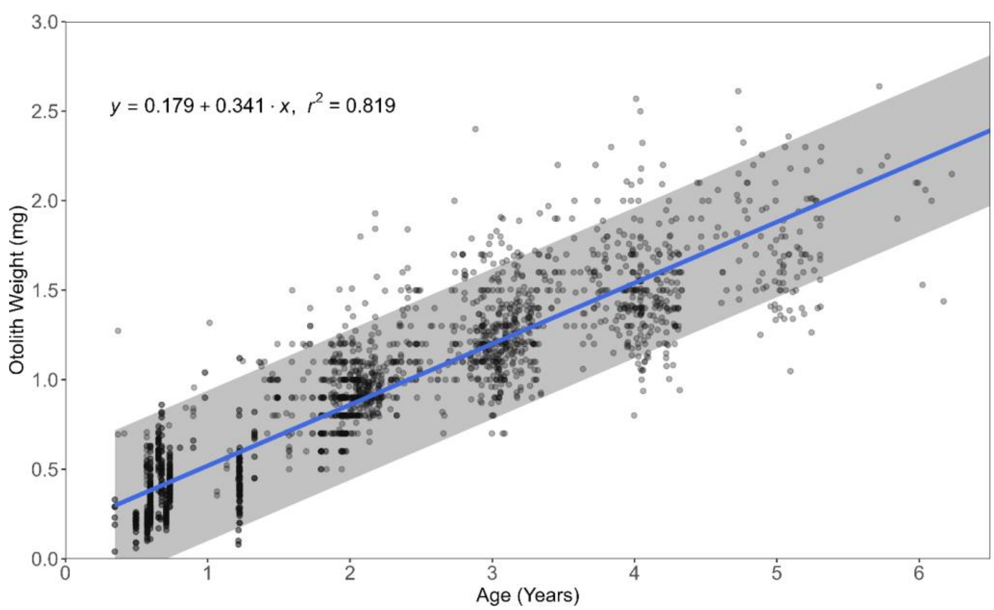


**Figure 3-2**. Regression of decimal age and otolith weight for Sardine otoliths with readability index scores of 1 and 2 from commercial and fishery-independent samples collected between 1995 and 2024. The light grey area represents 95% confidence intervals.

### 3.3.2 Age composition

Age composition data from commercial catches were available from 1995 to 2024, except for 2007 when no otoliths were collected. Ages ranged from 0+ to 8+ years. In 1995, fish aged 2+, 3+, and 4+ years dominated catches from the SG Zone, but from 1996 to 1998, catches were mostly dominated by age 1+ and 2+ fish, with a noticeable reduction of older fish in 1997 (Figure 3–3). These trends reflect the 1995 mass mortality event which mainly affected adult fish. In 1999, 2+ year olds (fish that were juveniles in 1998 and largely unaffected by the 1998 mass mortality event) dominated the catch. Fish that were spawned during 1997 and 1998 continued to dominate catches from the SG Zone as 2+ and 3+ year olds in 2000. From 2001 to 2024, 3+ year olds dominated the catch from the SG Zone in all years, except 2006, 2011 and 2019, when 2+ year olds were most abundant (Figure 3–3).

Catches from the Outside Zone generally comprised older fish compared to those from the two Gulf zones (Figure 3–4). In most years, fish aged 3+, 4+ and 5+ years dominated catches from the Outside Zone. However, fish aged 2+ years dominated catches in 1999, immediately after the 1998 mortality event, as well as in 2000. In 2019, 2+ year old fish were again the dominant year class with fewer older year classes present. Since 2021, the age composition once again comprised mostly 3+, 4+ and 5+ year olds.

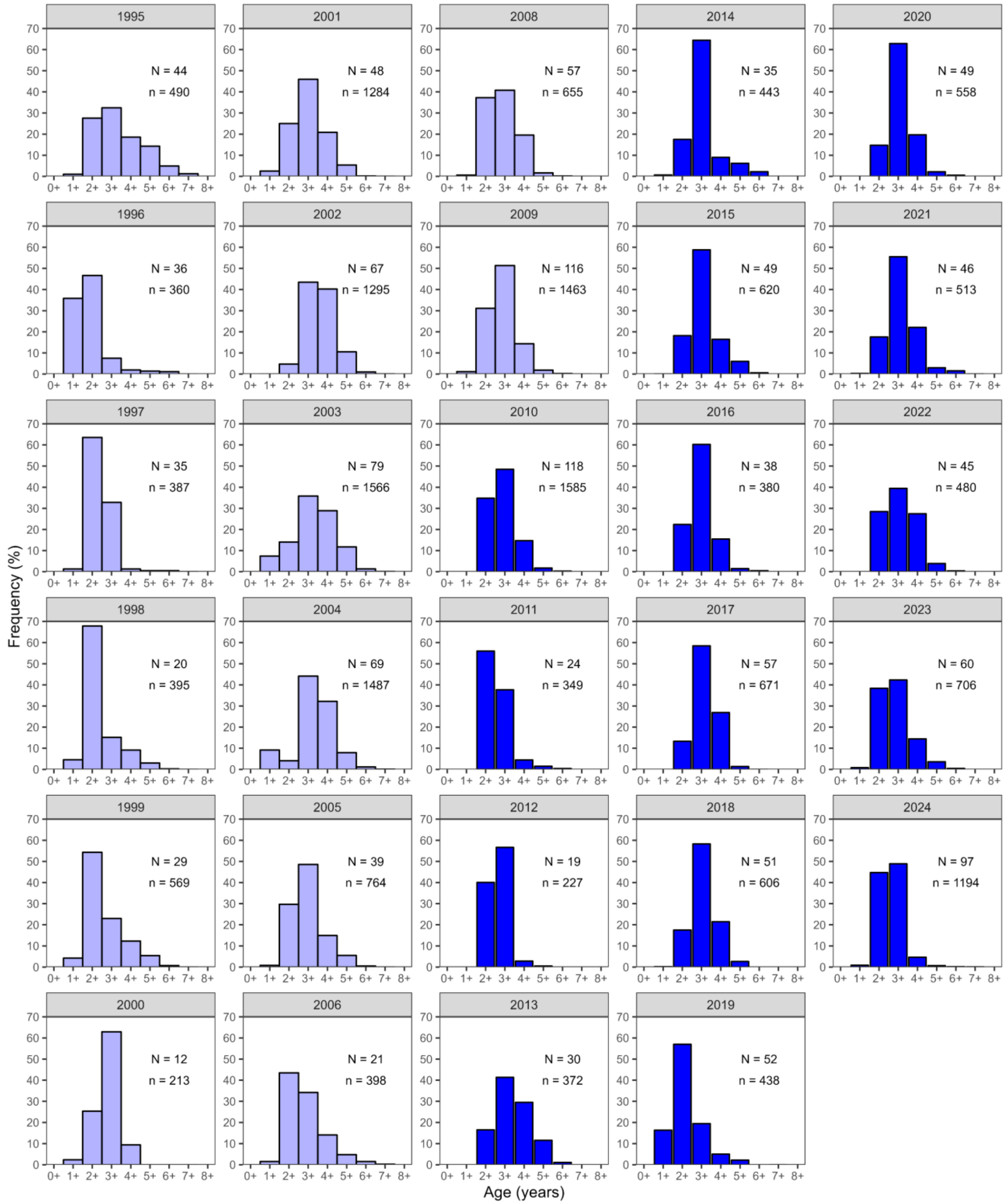


**Figure 3-3**. Age distributions for commercial catch samples of Sardine from the Spencer Gulf Zone between 1995 and 2024. Ages are derived from an otolith-weight-age relationship calculated for all years from otoliths with readability index scores of 1 and 2 and applied to all weighed otoliths for each year. Data were not available for 2007. Dark blue: catch weighted distributions; pale blue: not catch weighted. N: number of samples; n: number of fish.

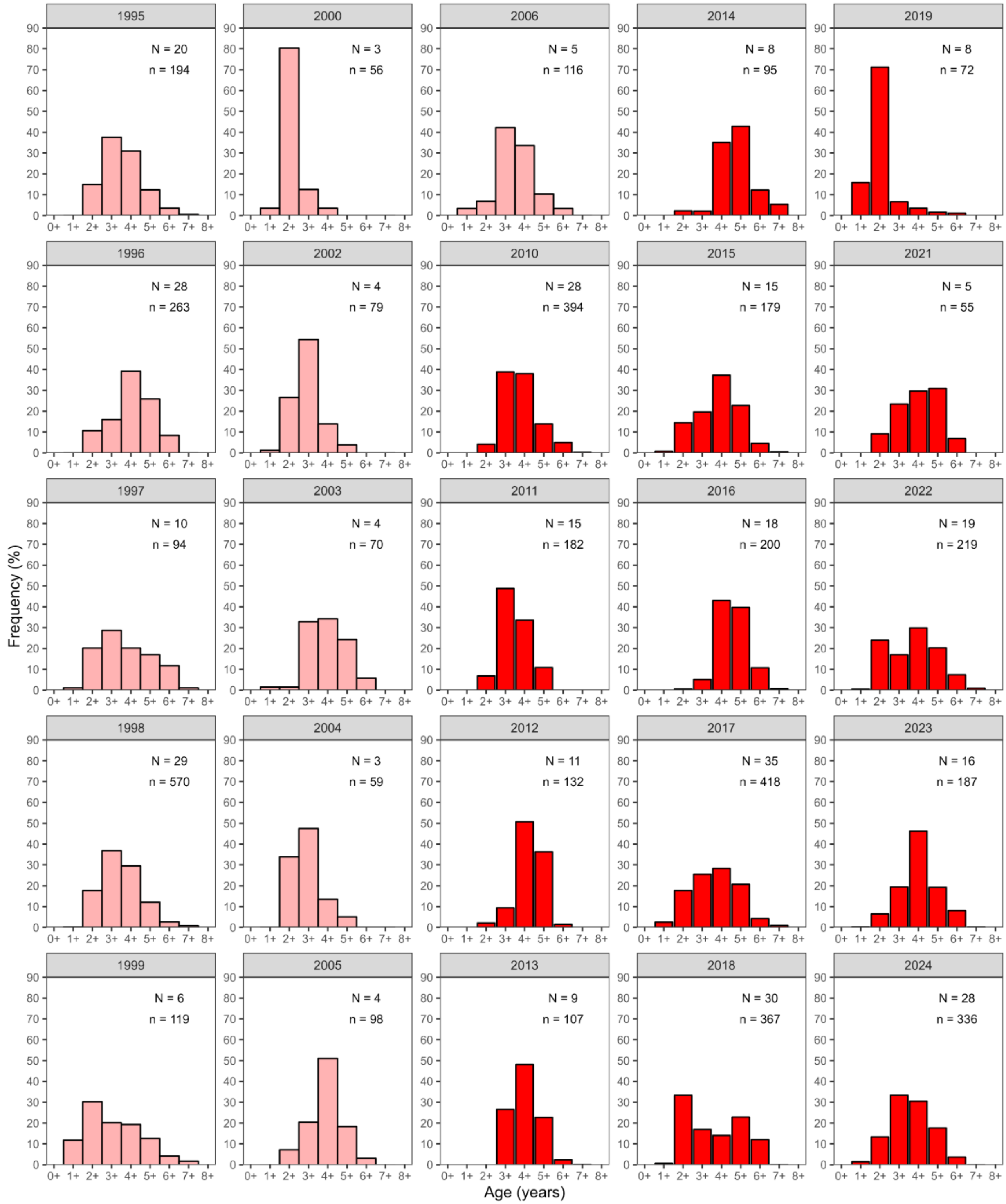


**Figure 3-4**. Age distributions for commercial catch samples of Sardine from the Outside Zone between 1995 and 2024. Ages are derived from an otolith-weight-age relationship calculated for all years from otoliths with readability index scores of 1 and 2 and applied to all weighed otoliths for each year. Data were not available from 2007 to 2009, and 2020. Bright red: catch weighted distributions; pale red: not catch weighted. N: number of samples; n: number of fish.

Between 2009 and 2011, catches from the GSV Zone were dominated by fish aged 2+ years. In 2016, fish aged 3+ year olds were more abundant before declining to 2+ years in 2017 (Figure 3–5). In 2018 and 2020, the age of Sardine from the GSV Zone was dominated by 4+ year olds. The age distribution of GSV Sardine showed a decline to a mode of 3+ years in both 2021 and 2022. However, in 2023, the age catch structure became bimodal, with peaks at 2+ and 4+ years. In 2024, the 2+ year age class was the most abundant. It is worth noting that the number of samples available from Gulf St Vincent was limited in most years.

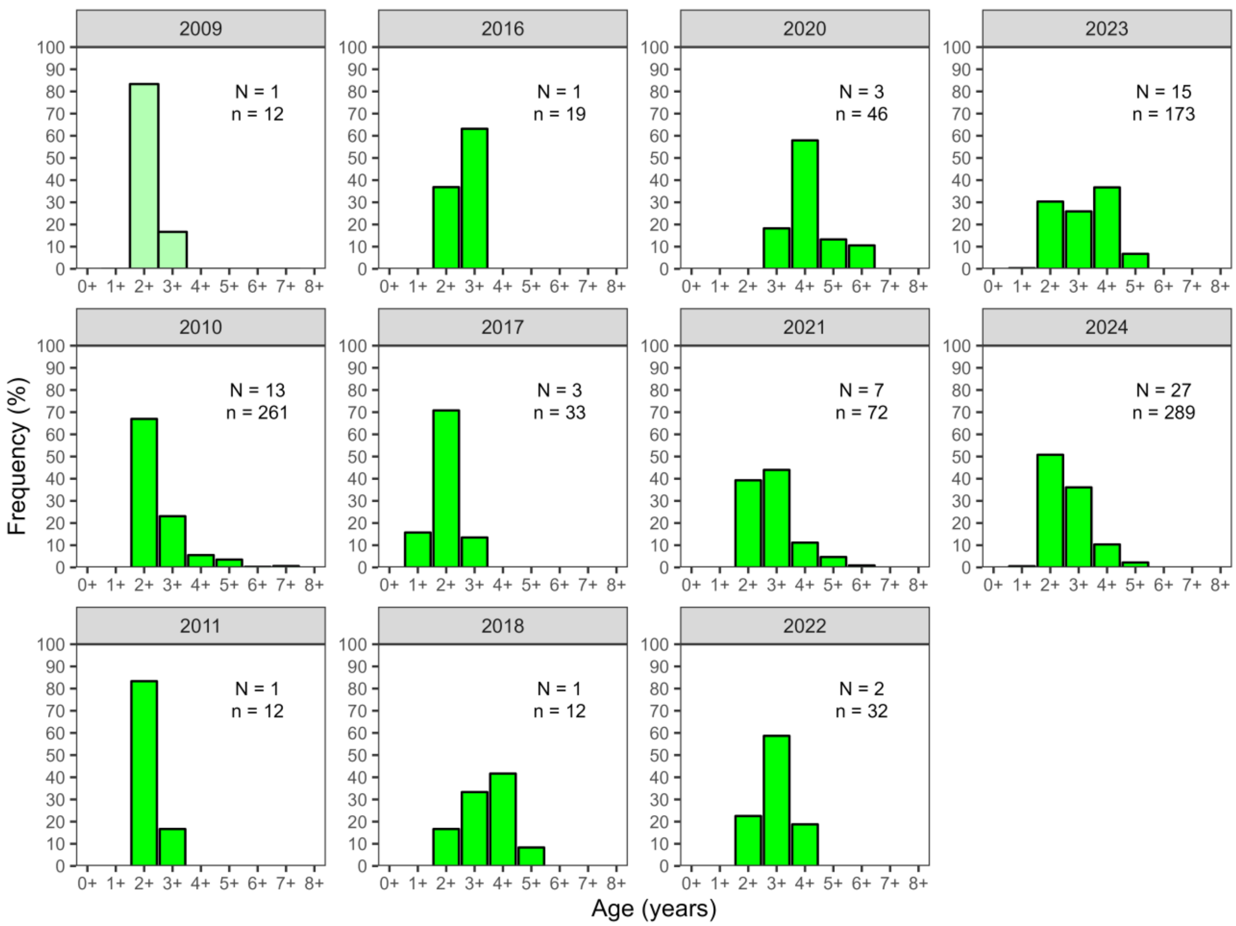


**Figure 3-5.** Age distributions for commercial catch samples of Sardine from Gulf St Vincent between 2009 and 2024. Ages are derived from an otolith-weight-age relationship calculated for all years from otoliths with readability index scores of 1 and 2 and applied to all weighed otoliths for each year. Bright green: catch weighted distributions; pale green: not catch weighted. N: number of samples; n: number of fish.

### 3.3.3 Growth

Fixing $t_0$ is a common approach for species whose life history includes a larval phase. The best fitting VBGF curve provided parameter estimates of: $L_\infty$ = 177.6 mm FL, $k$ = 0.7 year$^{-1}$, $L_0$ = 3.49 mm FL (Figure 3–6).

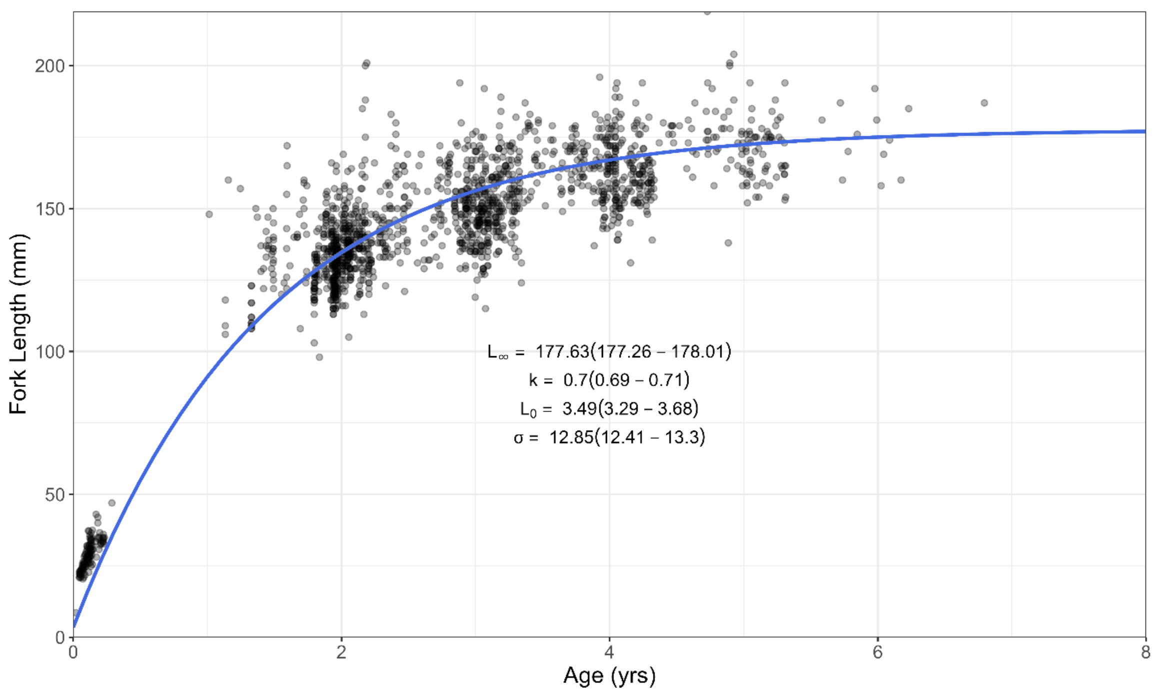


**Figure 3-6**. von Bertalanffy growth model fitted to length-at-age data (grey points; n = 1627) of individuals with otoliths that had readability index scores of 1 or 2 collected between 1995 and 2024.

### 3.3.4 Size-at-maturity

Size-at-maturity ($L_{50}$) estimated for Sardine from the commercial catch samples from the Gulf Zones (SG + GSV) between 1995 and 2024 has varied slightly among years (Figure 3–7). A declining trend in $L_{50}$ was apparent up to 2023 for both females and males, but reversed in 2024, with a slight increase toward the long-term mean (Figure 3–7). $L_{50}$ could not be estimated in 1998, 2007, 2012, 2013 and 2014 due to a lack of commercial samples collected during the spawning season. Samples from 2019 were too deteriorated to stage after a freezer break down. The interpretation of gonads for samples collected during 2020 appeared to be inconsistent with previous years and those data could not be used to determine $L_{50}$ in that year. All females below 118 mm FL and males below 116 mm FL had immature gonads. The estimate of $L_{50}$ using data from all years combined was 141.1 mm FL for females and 136.7 mm FL for males (Figure 3–8).

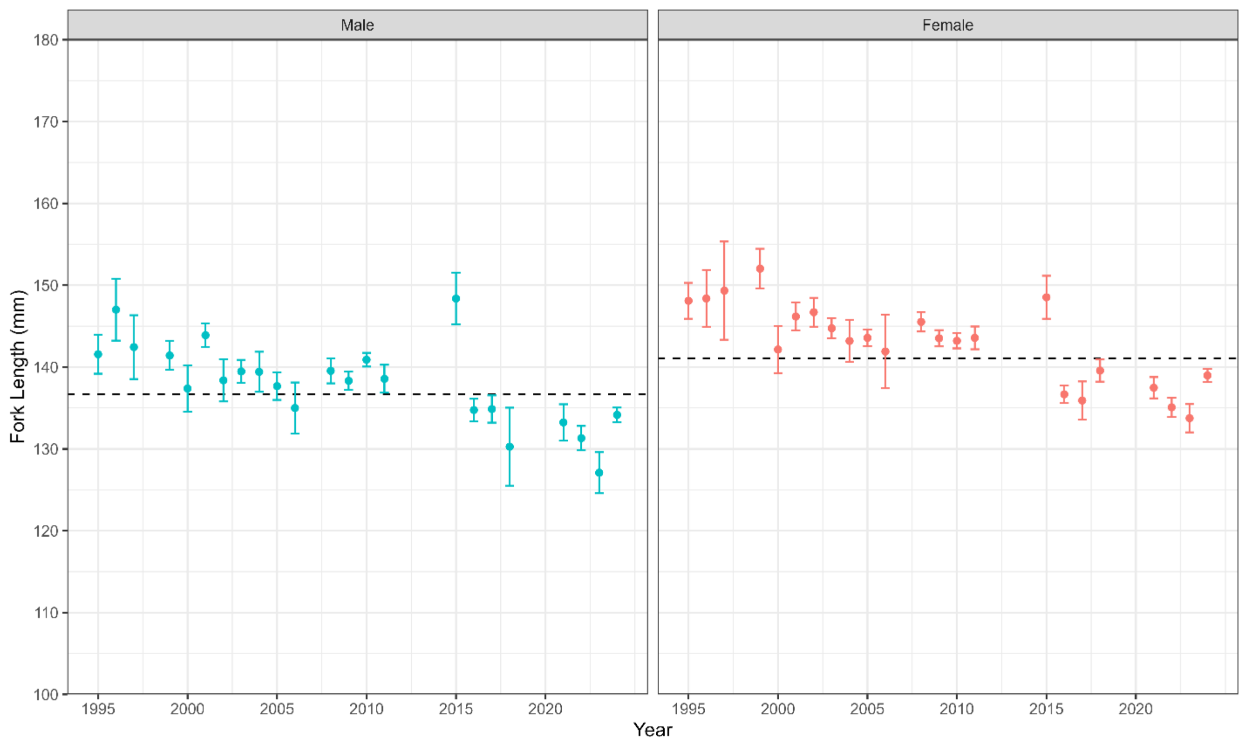


**Figure 3-7**. Size-at-maturity ($L_{50}$) for male and female Sardine collected in the two Gulf Zones (SG and GSV) by year, between 1995 and 2024. Some years were omitted due to low sample size and/or deteriorated samples. Error bars are 95% confidence intervals. Dashed lines represent the mean $L_{50}$ across all years calculated in Figure 3–8.

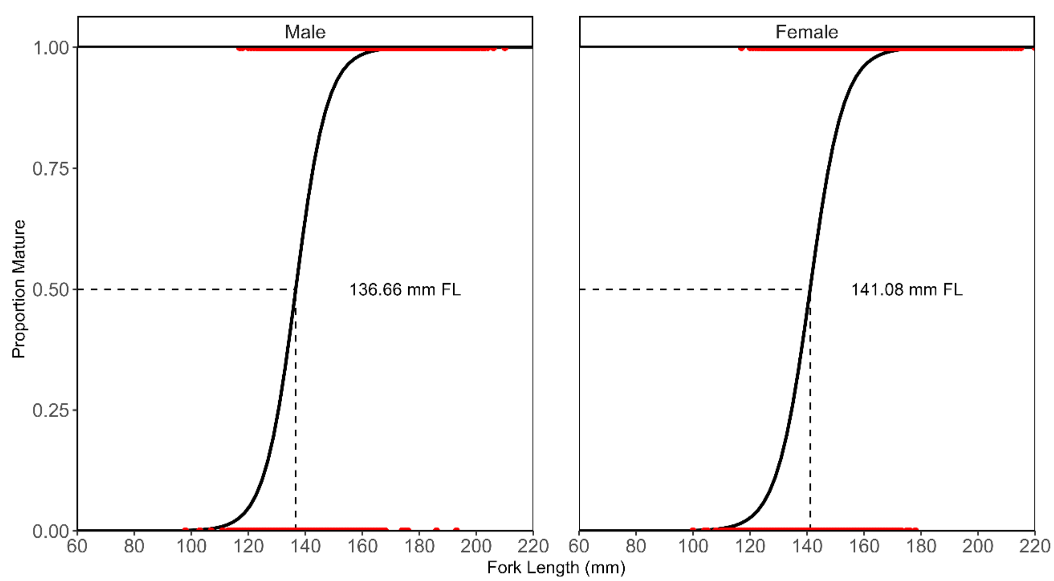


**Figure 3-8**. Size-at-maturity ($L_{50}$) for male and female Sardine collected from the two Gulf Zones (SG and GSV) for all years combined. Red: length ranges for mature (top) and immature (bottom) fish included.

### 3.3.5 Gonadosomatic index (GSI)

Seasonality of GSI varied among years (Figure 3–9). Sufficient samples to examine GSI were only obtained from the two Gulf zones in most years. GSI for both sexes peaked between November and April (Figure 3–9). Higher mean GSI values were observed for males than females, possibly due to male gonads not decreasing in size as much as females after each spawning event.

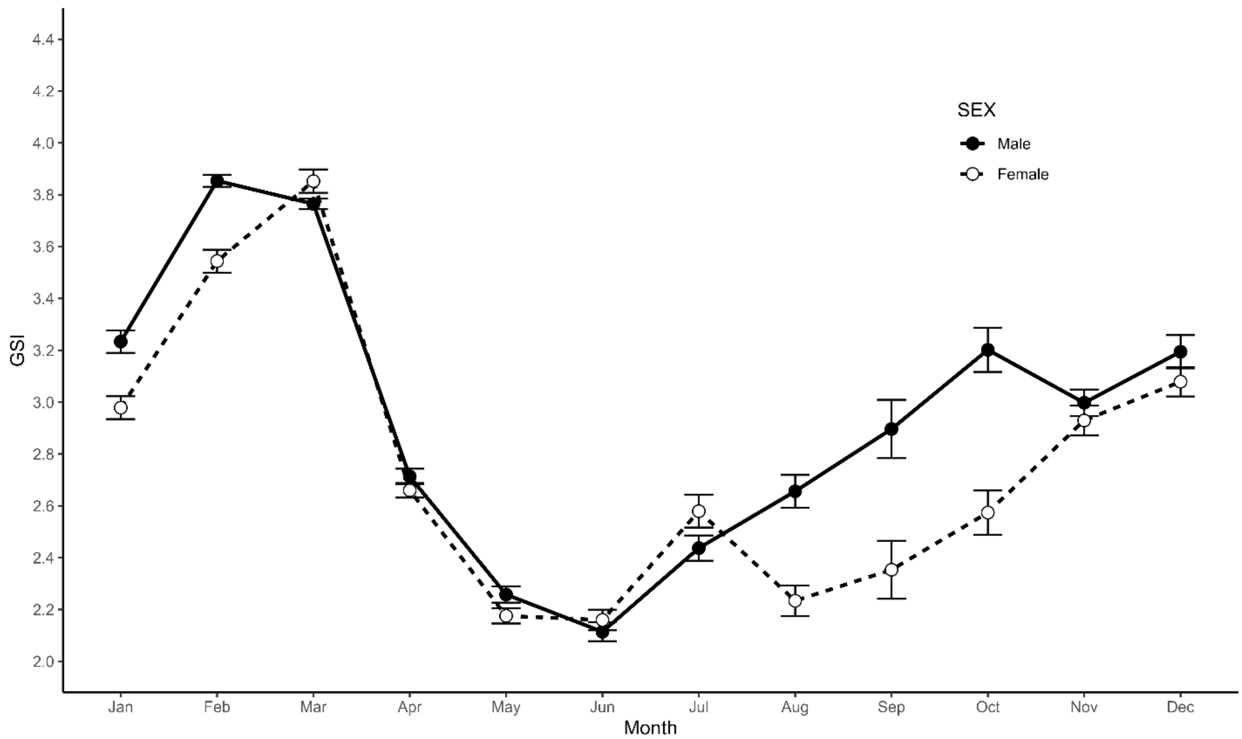


**Figure 3-9**. Mean monthly gonadosomatic index of male and female Sardine from commercial samples from the two Gulf Zones (SG and GSV) from 1995 to 2024, combined. Error bars are standard error. Fish below the size-at-maturity have been excluded.

## 3.4 Discussion

The relatively high level of uncertainty associated with estimating the age of Sardine from annual growth increments in otoliths has been noted previously (Fletcher et al. 1994, Rogers and Ward 2007). This issue can be partly overcome by using an age-otolith weight relationship developed from otoliths with high readabilities to estimate the age of Sardine with otoliths that are more difficult to read. However, this method requires a large number of otoliths to be read annually to ensure adequate numbers of otoliths with high readability. This approach should be applied with caution as the relationship between otolith weight and fish age is relatively imprecise. The use of alternative approaches to assigning ages warrants consideration.

The growth rates of individual Australian Sardine vary with age (Rogers and Ward 2007), with moderate to high growth rates occurring prior to sexual maturity and slower growth as adults. Several studies have shown limited modal progression in Sardine length data, whereas cohorts can be more reliably tracked using otolith weight (Fletcher et al. 1994, Rogers et al. 2004). This variability in growth rates limits the usefulness of age-length keys for estimating the age of Sardine.

Changes in management arrangements and fishing practices over the history of the fishery have likely driven changes in the age composition of catches. As a result, age composition data from commercial catches are unlikely to be representative of the total population, and size/age selectivity have likely changed over time, and these limitations need to be considered when interpreting the population model outputs (Chapter 5).

Despite these sampling limitations, a consistent pattern of the spatial distribution by size and age is emerging for the Southern Australia stock of Australian Sardine. Sardine taken from the Gulf Zones are usually younger and smaller than those taken from the Outside Zone (Figure 2–9). However, smaller and younger individual have been regularly caught off the southeast coast of Kangaroo Island in the Outside Zone since 2017 (SARDI unpublished data). Sardine taken from the most northerly fishing grounds in the SG and GSV Zones are also smaller and younger than those taken further south (Figure 2–9). These findings are consistent with observations for many species of small and medium-sized pelagic fishes (e.g. Australian anchovy, Jack Mackerel), where larger, older fish tend to be found in deeper waters and further offshore than smaller, younger fish (Dimmlich and Ward 2006, Sexton et al. 2017).

A coherent picture is also emerging in the temporal patterns in the size and age of Sardine taken from both Gulf Zones. In 1995, before the two mass mortality events, Sardine taken from Spencer Gulf had a modal age of 3+ years. From 1996 to 1999, the modal age was reduced to 2+ years but re-stabilised at 3+ years from 2000 to 2005. However, the modal age of Sardine taken from Spencer Gulf fell to 2+ years in 2006, after 38,734 t were taken from the Gulfs Zone (SG +GSV) in 2005. The modal age increased to 3+ years in 2008, before falling to 2+ years in 2011. The modal age returned to 3+ years from 2012 onwards, when rules capping the catch from the Gulfs Zone (SG + GSV) were introduced. As mentioned in the previous chapter, the mean size of fish taken from the Gulfs Zone (SG +GSV) in 2019 dropped below the reference size of 142 mm FL and caused a reduction in TACC in 2020 from 30,000 t to 27,000 t for the SG Zone. The larger (older) size (age) structures of fish taken from both Gulf Zones in most years since 2013 (except 2019 and 2024) suggests that the size-based decision rules were successful in reducing the capture of smaller-sized Sardine and preventing growth overfishing in the SASF.

The long-term declining trend in $L_{50}$ time series up to 2023, which was reversed in 2024, does not appear to result from changes in the size or age structure of the Sardine in the Gulf Zones, as no corresponding shifts in size or age structures were observed. While uneven catch sampling across the spawning season may have influenced this decline, it is unlikely to have been the main driver, given the trend was still apparent when $L_{50}$ was plotted by month across the time series (Grammer et al. 2024b). The cause of the $L_{50}$ decline remains unclear. It may reflect a genetic change to the population due to fishing (e.g. selectively targeting fish above the size at maturity; Rijnsdorp 1993, Grift 2003), a physiological response in the population to a change in environmental conditions (e.g. size at maturity declines with increasing water temperatures; Jonsson et al. 2013, Yoneda et al. 2015), or a combination of the two (Rijnsdorp 1993, Véron et al. 2020). These possibilities warrant further investigation.

# 4. SPAWNING BIOMASS OF SARDINE OFF SOUTH AUSTRALIA BETWEEN 1995 AND 2025

## 4.1 Introduction

This chapter presents the time series of spawning biomass for Sardine off South Australia for the period from 1995 to 2025. Data from the spawning biomass surveys in 2024 and February–April 2025 (Grammer et al. 2024a, Ivey et al. 2025) have been incorporated into the analyses. The estimates of spawning biomass are a key input into the population model in Chapter 5.

The Daily Egg Production Method (DEPM) was developed for stock assessment of the Northern Anchovy, *Engraulis mordax* (Parker 1985, Lasker 1985), and has been applied to more than 20 species of small to medium-sized pelagic fishes (e.g. Stratoudakis et al. 2006, Dimmlich et al. 2009, Neira et al. 2009, Grammer et al. 2022). The method is widely used in coastal fisheries because it is often the most practical option available for assessment of pelagic species (Ward et al. 1998). The DEPM has been used to estimate the spawning biomass of Sardine off South Australia since 1995 (Ward et al. 2021, Ivey et al. 2025).

The DEPM relies on the premise that spawning biomass can be calculated by dividing the mean number of pelagic eggs produced per day throughout the spawning area (i.e. total daily egg production) by the mean number of eggs produced per unit mass of adult fish (i.e. mean daily fecundity, Parker 1985, Lasker 1985). Total daily egg production is the product of mean daily egg production ($P_0$) and total spawning area ($A$). Mean daily fecundity is the product of mean sex ratio (by weight, $R$), mean spawning fraction (proportion of mature females spawning each day/night, $S$) and mean relative fecundity (number of eggs produced per gram of total female weight; $F'$). Spawning biomass ($SB$) is calculated according to the equation:

$$SB = P_0 * A/(R * S * F') \qquad \text{Equation 1}$$

The DEPM, as applied to Sardine off South Australia, underwent a comprehensive review in 2020 (Ward et al. 2021). This review reanalysed data collected between 1995 and 2019 for South Australian Sardine and identified several ways to increase the precision of estimates of spawning biomass: 1) increase the precision of total daily egg production ($P_0$*$A$) by using the estimate of $P_0$ obtained from all historical data rather than annual estimates of $P_0$; 2) continue to use the log-linear model to estimate $P_0$ for the Southern stock of Sardine; 3) increase the precision of mean daily fecundity ($R * S * F'$) by using the estimates of sex ratio ($R$), spawning fraction ($S$) and relative fecundity ($F'$) obtained from all historical data rather than annual estimates; and 4) combine batch fecundity (*F*) and female weight (*W*) into a single parameter: relative fecundity ($F' = \hat{F}/W$). The revised methods for the DEPM have been applied to estimates of spawning biomass for Sardine in South Australia since 2020 (Ward et al. 2021, Grammer et al. 2021, Grammer and Ivey 2023, Grammer et al. 2024a, Ivey et al. 2025).

## 4.2 Methods

### 4.2.1 Total daily egg production

*Ichthyoplankton surveys*

Ichthyoplankton surveys have been conducted from the *RV Ngerin* during the Sardine spawning season (January–April) off South Australia since 1995. Surveys were undertaken every year between 1995 and 2025, except 2008, 2010, 2012, 2015 and 2021. The 2025 survey was undertaken from February to April 2025. The orientation of transects and the number of sites sampled have varied among surveys (Figure 4–1). Changes in the area surveyed reflect the changes in the objectives of the sampling program over time. During 1995- 97, the primary goal was to identify the main spawning grounds and develop an appropriate survey design. The sampling design and area sampled continued to be refined from 1998 to 2004, primarily to ensure adequate coverage of the spawning (Figures 4–1). During 1995 and 1996, when the primary goal was to identify areas where Sardine spawned, transects were orientated from north to south and relatively few sites were sampled. After 1997, transects were orientated from north-east to south-west to improve sampling efficiency. From 1998 onwards, there has been a general increase in the number of sites sampled during each survey. From 2006 onwards, the number of sites sampled in Spencer Gulf has doubled.

An adaptive approach to egg sampling has been applied since 2014 to ensure that each survey covered as much of the spawning area as possible (see Ward et al. 2017). Under this adaptive sampling protocol, additional samples have been taken at sites located outside the area covered by the historical, pre-determined sampling sites (Figure 4–1). Decisions about whether to take additional samples were based on the presence/absence of eggs in samples taken using the Continuous Underway Fish Egg Sampler (CUFES) at sites located on the seaward end of transects. Sampling at additional sites continued until Sardine eggs were not present in the CUFES samples.

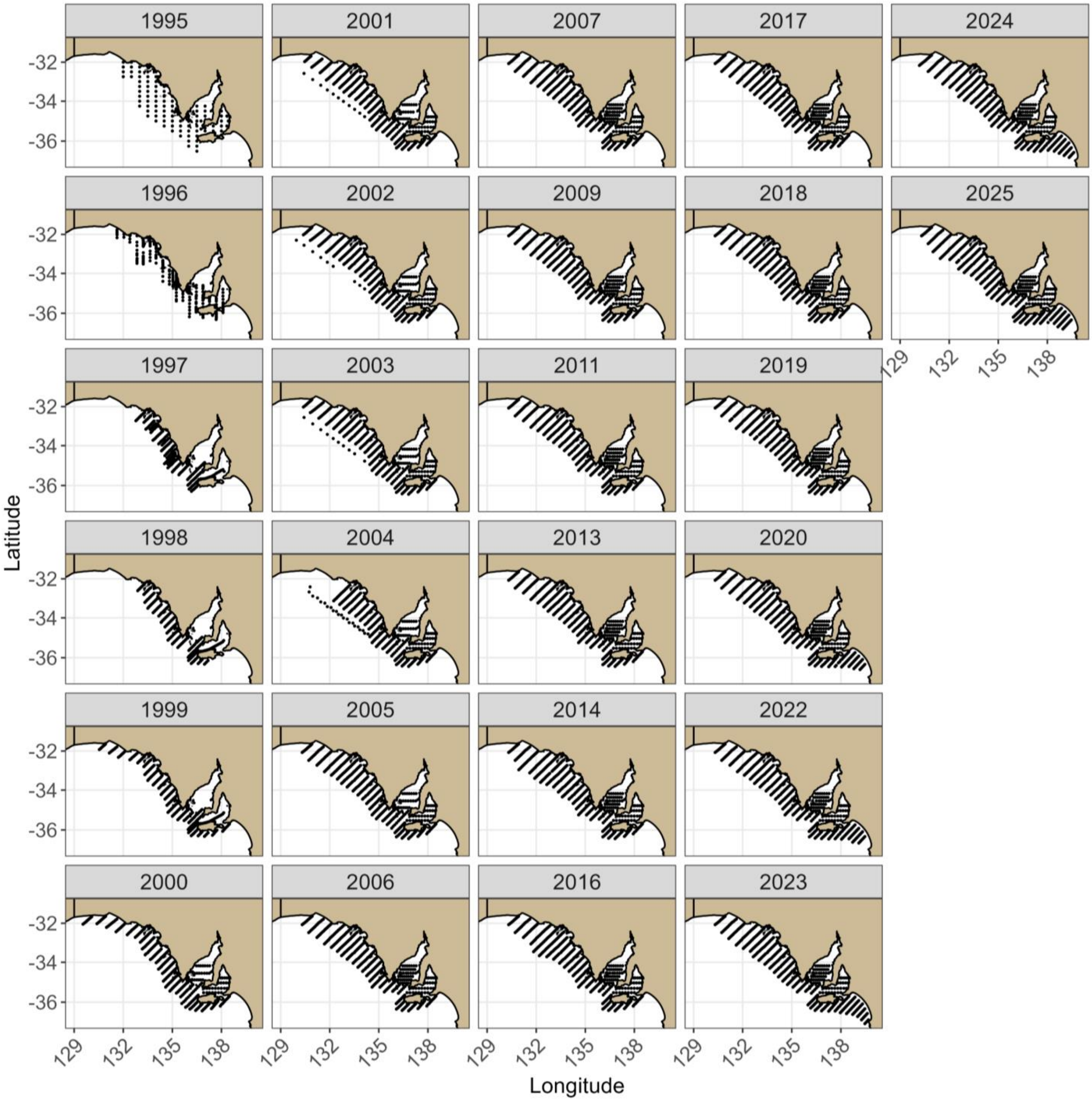


**Figure 4-1.** Location of sites sampled during ichthyoplankton surveys conducted off South Australia between 1995 and 2025.

Since 2020, additional transects have been added to the south-eastern end of the survey to the east of Kangaroo Island, and along the outer end of transects in the GAB. The south-eastern sites were added in response to the expansion of the fishery into this region and recent observations that Sardine eggs had become more common in the area (Ward et al. 2020a; Figure 4-1). The predetermined survey design has remained the same since 2023. In 2025, 22 extra sites were sampled on the seaward ends of 16 transects in response to eggs being present in the CUFES (Ivey et al. 2025).

Samples were collected at each site in each year as shown in Figure 4-1 using paired Californian Vertical Egg Tow (CalVET) plankton nets. The CalVET nets have an internal diameter of 0.3 m, 330 µm mesh and plastic cod-ends. During each tow, the nets were deployed to within 10 m of the seabed at depths <80 m or to a depth of 70 m at depths >80 m. Nets were retrieved vertically at a speed of ~1 $m.s^{-1}$. A *Sea-Bird* Conductivity-Temperature-Depth (CTD) profiler attached to the CalVET nets was used to measure oceanographic parameters (e.g. temperature, salinity, fluorescence) at each site. General Oceanics™ flowmeters were used to estimate the distance travelled by each net. Samples from the two cod-ends were combined and stored in 5% buffered formaldehyde and seawater solution.

*Egg identification and staging*

Sardine eggs were identified using published descriptions (Neira et al. 1998, White and Fletcher, 1998). Eggs were classified into developmental stages based on the descriptions by White and Fletcher (1998). Total counts of eggs of each developmental stage in each sample were recorded. Eggs in the first and last stages were excluded from the statistical analyses because they can be under- and over-represented in plankton samples, respectively (Ward et al. 2018).

*Egg ageing, treatment of zero count egg samples and egg density*

The development rate of Sardine eggs is dependent on ambient water temperature (Picquelle and Stauffer 1985, Pauly and Pullin 1988). Based on the temperature data from the CTD, egg samples were allocated to one of three temperature bins that covered the range of temperatures encountered during surveys (14–18°C, 18–22°C, and 22–26°C). The temperature bins were comparable to those used by Le Clus and Malan (1995) to describe the developmental rates of Sardine eggs. These published development rates were used to assign a mean age to each egg in each sample (see Ward et al. 2018).

After each egg was assigned an age, the eggs in each sample were grouped into daily cohorts. This was done because a sample usually included eggs spawned on more than one night. The total number of eggs in each daily cohort was calculated by summing the number of eggs of each stage assigned to a spawning day (i.e. day 0, day 1, day 2). The age of a daily cohort was calculated from the average age of each stage within the daily cohort, weighted by the number of eggs in each stage.

Samples with eggs could contain several possible combinations of daily cohorts depending on water temperature, spawning time (peak around 2:00 am) and sampling time. Zero counts were allocated for daily cohorts where the cohort was expected to be present but was not found within the sample (Ward et al. 2018). Samples with no eggs were excluded from the analyses and not considered part of the spawning area. The number of eggs of each stage under one square metre of water ($P_t$) was estimated at each site according to Equation 2 (Table 4-1).

*Spawning area*

The spawning area (*A*) was estimated for each survey (Lasker 1985, Somarakis et al. 2004) using the Voronoi natural neighbour method (Watson 1981). The survey area was divided into a series of contiguous polygons approximately centred on each site using the 'deldir' package in the statistical program R (R Core Team 2024, Turner 2023). The area represented by each site ($km^2$) was calculated. *A* was defined as the total area of the polygons where live Sardine eggs were present in the plankton sample (see Fletcher et al. 1996).

*Mean Daily Egg Production ($P_0$)*

The underlying model used to calculate mean daily egg production ($P_0$) was the exponential egg mortality mode with a bias correction factor (the 'log-linear model'). A linear version of the exponential egg mortality model was fitted to estimates of egg age and density for each daily cohort at each site (Picquelle and Stauffer 1985; Equation 3, Table 4-1).

Estimates of $P_b$ from the log-linear version of the exponential mortality model have a negative bias, therefore a bias correction factor was applied (Equation 4, Table 4-1). This equation is hereafter referred to as the 'log-linear model'.

A general linear model (GLM) with a negative binomial error structure (NB1), was also used to estimate $P_0$ (Equation 5, Table 4-1). The negative binomial error structure used is considered suitable for over-dispersed data, such as egg density by age (e.g. Ward et al. 2011, 2018, 2021). For NB1, variance increased linearly with the mean ($\sigma = \mu^*(1+ \mu +\varphi)$), where $\mu$ is the model estimate, σ is the model variance and φ is the over-dispersion parameter. The GLM used a log-link function (Wood 2006) and was fit using the glmmTMB R package (Brooks et al. 2017). Estimates of $P_0$ and $z$ obtained by fitting the two models to egg data collected each year and to data obtained in all years from 1998 to 2025 (combined) are presented in Appendix A (Table A3).

**Table 4-1**. Equations used when applying the DEPM to estimate the spawning biomass of Sardine.

| Calculation | Equation | Eq. no. | Parameters | Reference |
|---|---|---|---|---|
| Egg Density (sample) | $P_s = \frac{C\ D}{V}$ | 2 | $P_s$: density of eggs in a sample<br>$C$: number of eggs of each age in each sample<br>$V$: volume of water filtered (m$^3$)<br>$D$: depth (m) of net cast | Smith and Richardson (1977) |
| Negatively biased estimate ($P_b$) | $\ln P_b = \ln(P_{i,t} + 1) - Zt$ | 3 | $P_b$: negatively biased $P_0$<br>$P_{i,t}$: density of eggs of age $t$ at site $i$<br>z: instantaneous rate of daily egg mortality | Picquelle and Stauffer (1985) |
| Bias corrected ($P_0$) | $P_0 = e^{\left(\ln P_b + \sigma^2/2\right)} - 1$ | 4 | $P_b$: negatively biased estimate of daily egg production<br>$\sigma^2$: variance of $P_b$ estimate | Wood (2006), Ward et al. (2011, 2018) |
| Generalised Linear Model (GLM) with negative binomial error structure | $E[P_0] = g^{-1}(-zt + \varepsilon)$ | 5 | E[$P_0$]: expected value of $P_0$<br>$g^{-1}$: inverse-link function<br>*zt*: the instantaneous rate of daily egg mortality at age *t*<br>ε: error term | Wood (2006), Ward et al. (2011, 2018) |
| Female Weight | $W = \overline{\left[\frac{\overline{W_i}\, n_i}{N}\right]}$ | 6 | $\overline{W_i}$ : mean female weight of each sample *i*;<br>*n*: number of fish in each sample<br>*N*: total number of fish collected in all samples | Lasker (1985) |
| Sex Ratio: sample | $\overline{R_i} = \frac{F_i}{F_i + M_i}$ | 7 | $F_i$: total weight of mature females in each sample *i*<br>$M_i$: total weight of mature males in each sample *i* | Lasker (1985) |
| Sex Ratio: population | $R = \overline{\left[\frac{\overline{R_i}\, n_i}{N}\right]}$ | 8 | $\overline{R_i}$ : mean sex ratio of each sample *i*<br>*n*: number of fish in each sample *i*<br>*N*: total number of fish collected in all samples | Lasker (1985) |
| Spawning Fraction: sample | $\overline{S_i} = \frac{d0 + d1 + d2}{3\ n_i}$ | 9 | *d*0, *d*1 and *d*2: the number of mature females with POFs aged day 0, 1 or 2 in each sample<br>$n_i$: is the total number of females within a sample. | Lasker (1985) |
| Spawning Fraction: population | $S = \overline{\left[\overline{S_i} * \frac{n_i}{N}\right]}$ | 10 | $\overline{S_i}$: mean spawning fraction of each sample *i*<br>*n*: number of fish in each sample *i*<br>*N*: total number of fish collected in all samples | Lasker (1985) |

## 4.2.2 Mean daily fecundity

*Adult parameters*

Adult parameters used to calculate spawning biomass are derived from all adult samples of Sardine collected for DEPM surveys off South Australia between 1995 and 2024 (see Grammer et al. 2024a).

*Adult sampling*

Mid-water trawling and sampling from commercial catches undertaken during 1995–1997 did not provide samples suitable for estimating adult reproductive parameters of Sardine off South Australia. The lack of reliable estimates of these adult parameters reduced the reliability of estimates of spawning biomass obtained during this period (e.g. Ward et al. 2001a).

From 1998 to 2024, fishery independent samples of mature Sardine were collected from sites located in the eastern Great Australian Bight, southern Spencer Gulf and Investigator Strait using a gillnet (Figure 4-2). In the late afternoon, a dual frequency echo sounder (60 and 180 KHz) was used to search areas where schools of adult Sardine were known to aggregate. A gillnet comprising three panels, each with a different multi-filament nylon mesh size (*Double Diamond*: 210/4 ply meshes 25, 28 and 32 mm; Ward and McLeay 1998) was deployed from the port side of the *RV Ngerin* at protected locations where schools were encountered. Surface and sub-surface lights (150 W) were illuminated near the net after it was set. Net soak times varied from 15 minutes to 3 hours depending on the number of fish caught.

After the net was retrieved, fish were removed and dissected immediately. All Sardine collected were counted and sexed. Mature males and immature fish were frozen. Mature females were fixed in 10% buffered formaldehyde seawater solution.

In 2024, the South Australian Sardine Industry Association (SASIA) collected fishery-dependent samples from selected purse seine net-sets during commercial fishing operations, targeting sets where spawning Sardine were likely to be encountered. Sampling procedures were consistent with those used for the fishery independent sampling (described above), where fish in each sample were counted and immediately dissected, sexed, and either preserved or frozen. All samples were then sent to SARDI Aquatic Sciences for subsequent processing and analyses.

*Female weight (W) and Male weight*

Mature females from each sample were removed from the formalin solution and weighed (± 0.01 g). Fixation in formalin has negligible effect on fish weight (Lasker 1985). The mean weight of mature females in the population was calculated from the average of sample means weighted by proportional sample size (Equation 6, Table 4-1). Mature males in each sample were thawed and weighed (± 0.01 g).

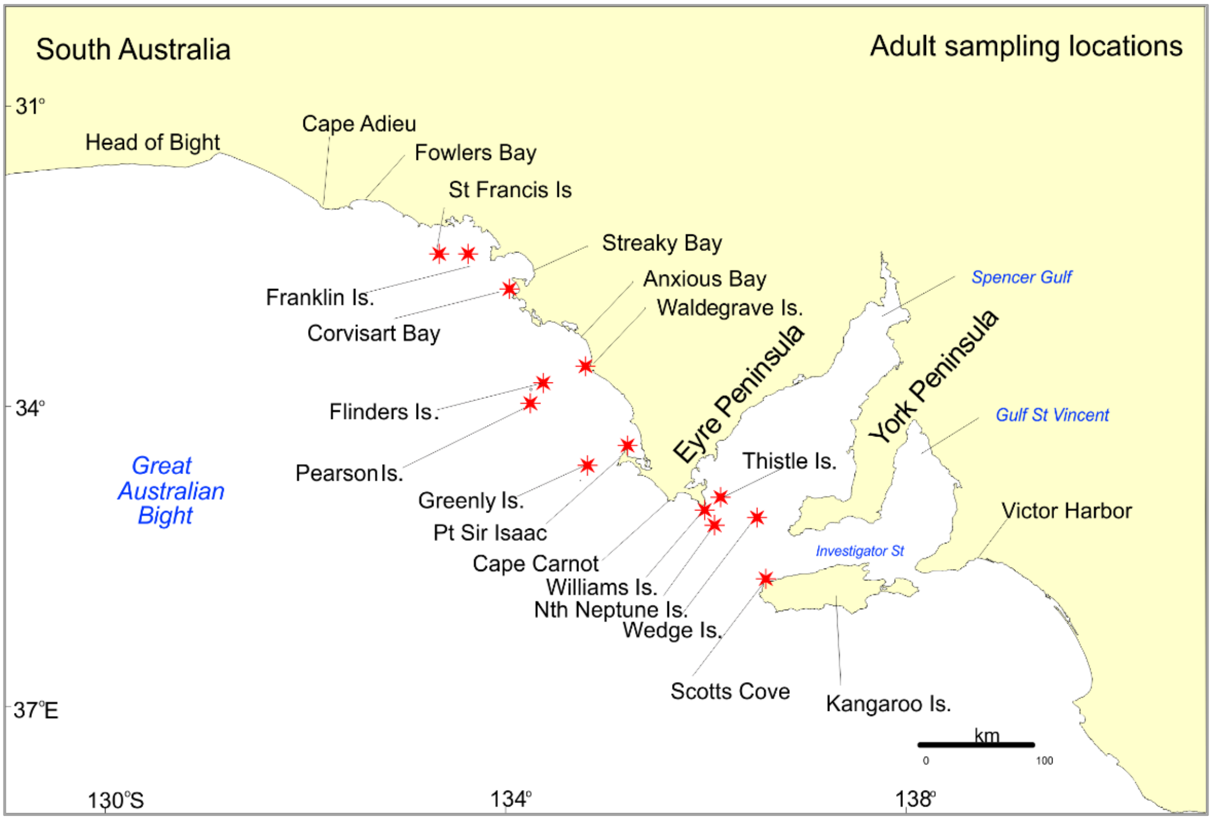


**Figure 4-2.** Location of sampling sites for adult Sardine off South Australia.

*Sex ratio (R)*

The mean sex ratio of mature individuals in the population was calculated from the average of sample means weighted by sample size (Equations 7 and 8, Table 4-1).

*Spawning fraction (S)*

Ovaries of mature females were sectioned and stained with haematoxylin and eosin. Several sections from each ovary were examined to determine the presence/absence of post-ovulatory follicles (POFs). POFs were aged according to the criteria developed by Hunter and Goldberg (1980) and Hunter and Macewicz (1985). The spawning fraction of each sample was estimated as the mean proportion of females with hydrated oocytes plus day-0 POFs (*d*0) (assumed to be spawning or have spawned on the night of capture), day-1 POFs (*d*1) (assumed to have spawned the previous night) and day-2 POFs (*d*2) (assumed to have spawned two nights prior). The mean spawning fraction of the population was then calculated from the average of sample means weighted by proportional sample size (Equations 9 and 10, Table 4-1).

*Batch fecundity*

Batch fecundity (*F*) was estimated from ovaries containing hydrated oocytes using the methods of Hunter and Macewicz (1985). Both ovaries were weighed and the number of hydrated oocytes in three weighed ovarian sub-sections counted. The total batch fecundity for each female was calculated by multiplying the mean number of oocytes per gram of ovary segment by the total weight of the ovaries. Methods to estimate the batch fecundity for mature females without hydrated ovaries ($\hat{F}$) followed those of Ward et al. (2021).

Relative Fecundity (*F'*) was calculated by dividing batch fecundity ($\hat{F}$) determined for data from all years (1998-2024) by total female weight (*W*).

### 4.2.3 Spawning biomass

Spawning biomass was calculated using the all-years estimate of $P_0$ (1998 to 2025) obtained from the log-linear model (Ivey et al. 2025), spawning area (*A*) in each year and estimates of *S, R* and *F'* obtained from adult samples collected between 1998 and 2024 (Grammer et al. 2024a).

The reliability of model fits, 95% confidence intervals (CIs) and coefficients of variation (CVs) for $P_0$ were estimated using bootstrap resampling methods with 10,000 iterations. Coefficients of variation and CIs for *R, S, F, W* and *F'*, were calculated from the all-years adult data. *A* ratio estimator was used to calculate the variance for *S, R*, and *F'* (Rice 1995). Variances for the spawning biomass estimates were calculated by summing the squared CVs for each parameter and multiplying by the square of the estimate of spawning biomass (Parker 1985). Uncertainty estimates presented for all parameters are 95% CIs. Data analyses were done in the R programming environment (R Core Team 2024).

Sensitivity analyses were conducted to assess the effects of variations in the range of values obtained for each parameter in each year between 1998 and 2025 on the estimate of spawning biomass for 2025. The results of the sensitivity analysis are presented in Ivey et al. (2025).

## 4.3 Results

### 4.3.1 Total daily egg production

*Total area sampled*

The total area sampled during the ichthyoplankton surveys varied from 48,379 km$^2$ in 1998 to 140,900 km$^2$ during February–April 2025 (Figure 4–3). The total survey area was consistently about 119,000 km$^2$ from 2006 to 2013. Total survey area increased in 2014 to 125,249 km$^2$, after the adaptive sampling protocol was implemented in response to the incomplete coverage of the spawning area in 2013 (Figure 4–4b). Since 2020, the survey has expanded to 140,900 km$^2$ in 2025 (Ivey et al. 2025) to include shelf waters between Kangaroo Island and Kingston in response to an expansion of the fishery into this area (Figures 4–1, 4–4b). Adaptive sampling remains a key element of the current survey design and is also a reason the total survey area varies slightly from year to year.

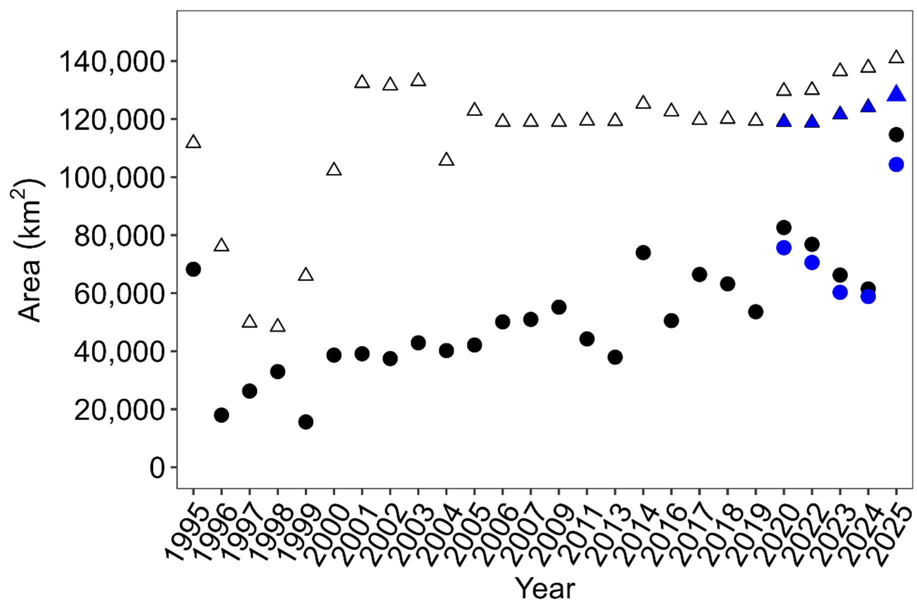


**Figure 4-3.** Total area sampled (km$^2$) (triangles) and corresponding spawning area (*A,* km$^2$) (circles) for DEPM surveys from 1995 to 2025. For comparison: blue points for *A* exclude additional sites added since 2020.

*Spawning area (A)*

Estimates of spawning area varied among years and reflected both the size of the survey area and the spawning biomass. The spawning area declined substantially following the two mass mortality events, from 68,260 km$^2$ in 1995 to 17,990 km$^2$ in 1996, and from 32,980 km$^2$ in 1998 to 15,637 km$^2$ in 1999 (Figure 4-3). Between 2000 and 2005, the spawning area remained between 37,000 and 42,200 km$^2$, before increasing to > 50,000 km$^2$ from 2006 to 2009. In 2011 and 2013, the spawning area was below 45,000 km$^2$ but the 2013 survey did not cover the entire spawning area as the stock had moved offshore. Spawning area increased to 73,900 km$^2$ in 2014 and remained above 50,000 km$^2$ from 2015 to 2019 (Figure 4–3). Spawning area increased to

82,600 km$^2$ in 2020. The spawning area was 61,000–77,000 km$^2$ from 2021 to 2024, before increasing to 114,640 km$^2$ in 2025 (Figure 4–3). If the additional stations added to the main survey since 2020 had not been included, the estimated spawning area in 2025 would have been 104,357 km$^2$, which is the highest estimate on record.

*Egg distribution and abundance*

The distribution and abundance of Sardine eggs has varied considerably among years. Areas where large numbers of eggs are sometimes found include shelf waters of the eastern Great Australian Bight, between Coffin Bay and the Head of Bight, southern Spencer Gulf, and the western end of Investigator Strait (Figures 4–4a and 4–4b). Large numbers of eggs regularly occur to the south and east of Kangaroo Island. Mass mortality events in 1995 and 1998 reduced both the total abundance of eggs and their spatial distribution off South Australia (see Ward et al. 2001a). The presence of eggs in offshore waters in 2013 was a major change from the historical patterns. In 2024, a large upwelling event likely reduced the available spawning habitat. During February–April 2025, sites with high egg densities were observed across most of the survey area, including southern Spencer Gulf, throughout the GAB, south of Kangaroo Island, and in the south-east region. Eggs were also widespread throughout Investigator Strait. Sites where live eggs were not detected occurred along the northern transects in both Gulfs and the inshore stations near Victor Harbor.

*Mean daily egg production ($P_0$)*

The estimate of $P_0$ obtained by fitting the log-linear model to all data from 1998 to 2025 was 88.7 (95% CI: 80.8–97.3) eggs.day$^{-1}$.m$^{-2}$ (Ivey et al. 2025). The estimate of $P_0$ obtained by fitting GLM NB1 to all data from 1998 to 2025 was 103.3 (95% CI: 90.8–119.0) eggs.day$^{-1}$.m$^{-2}$ (Ivey et al. 2025). Estimates of $P_0$ for individual years (log-linear model) ranged from 39.0 in 2013 to 152.6 in 2024 (Table A3).

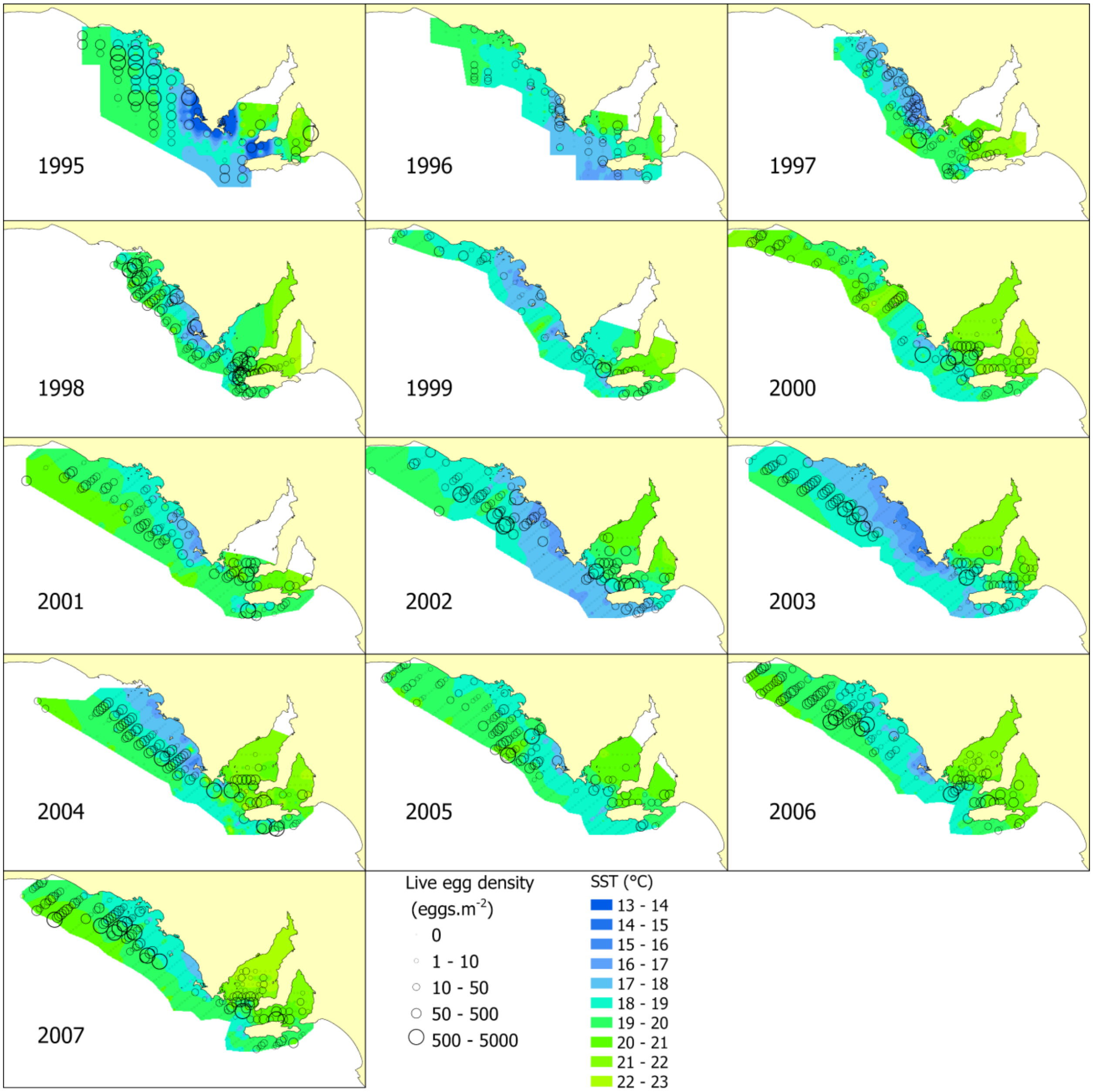


**Figure 4-4a**. Distribution and abundance of Sardine eggs collected during surveys between 1995 and 2007, overlaid on sea surface temperatures (SST) data.

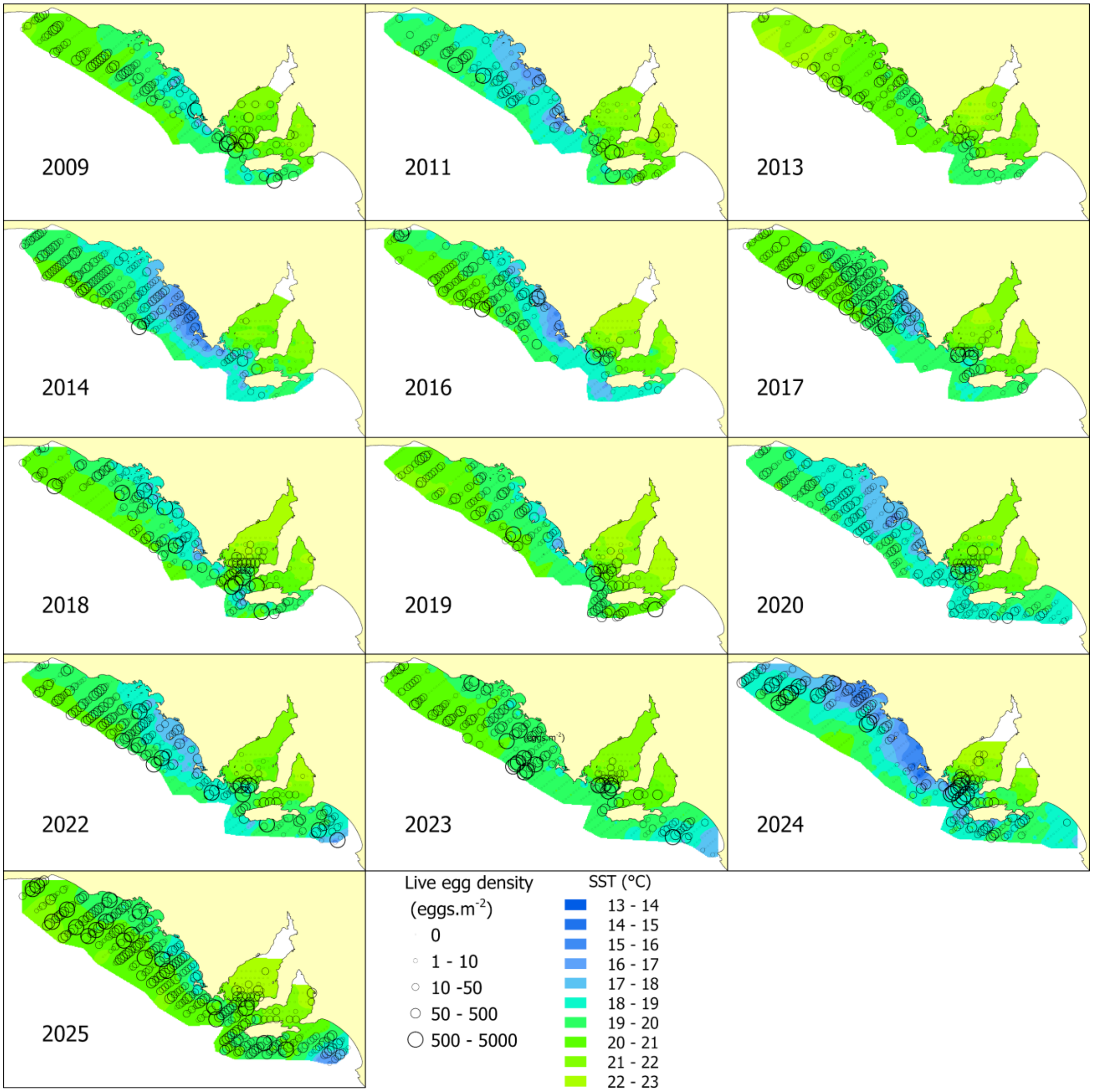


**Figure 4-4b**. Distribution and abundance of Sardine eggs collected during surveys between 2009 and 2025, overlaid on sea surface temperatures (SST) data.

### 4.3.2 Adult parameters

Mean female weight

The mean weight of mature females (*W*, 95% CI) estimated from 17,210 fish (271 samples) collected between 1998 and 2024 was 58.3 g (23.1–93.4) (Grammer et al. 2024a). Estimates of *W* for individual years ranged between 46.5 g in 1998 and 78.7 g in 2004 (Table A3).

Sex ratio

The mean sex ratio by weight (*R*, 95% CI) calculated from all fish collected between 1998 and 2024 was 0.53 (0.50–0.56) (Grammer et al. 2024a). Estimates of *R* for individual years ranged from 0.36 in 2009 to 0.70 in 2018 (Table A3).

Batch fecundity

Between 1998 and 2024, 1,176 females with hydrated oocytes were collected (Grammer et al. 2024a). The fecundity-weight relationship estimated from these samples was: Batch Fecundity = 334 × Gonad Free Female Weight – 558 ($R^2$ = 0.52) (Grammer et al. 2024a). Overall mean batch fecundity ($\hat{F}$, 95% CI) was 17,967 (3,802–32,131) oocytes (Table A3).

Relative Fecundity (Eggs per gram of mature female weight (*F'*))

The overall estimate of *F'* was 308.4 (95% CI: 307.2–309.6) eggs.$g^{-1}$ (Grammer et al. 2024a). Estimates of *F'* for individual years ranged from 298.3 eggs.$g^{-1}$ in 2000 to 316.2 eggs.$g^{-1}$ in 2011 (Table A3).

Spawning fraction

The spawning fraction (*S*, 95% CI) calculated from a total of 17,210 ovaries were examined between 1998 and 2024 was 0.111 (0.100–0.122) (Grammer et al. 2024a). Estimates of *S* for individual years ranged from 0.041 in 2014 to 0.179 in 2001 (Table A3).

### 4.3.3 Spawning biomass

Estimates of spawning biomass obtained through the application of the DEPM over time were improved by the re-analysis of historical data (Grammer et al. 2024a). In particular, the estimates of adult parameters obtained from data collected from 1998 to 2024 helped to resolve uncertainties in estimates of mean daily fecundity for 1995 to 1997 that were driven by the limited number of adult samples collected during this initial period. Similarly, the preliminary estimates of

$P_0$ obtained from the limited plankton sampling undertaken in the early years of this time series were likely improved by applying refined analytical methods.

The overall estimate of $P_0$ (88.7 eggs.day$^{-1}$.m$^{-2}$; log-linear model) was updated for 2025 using egg data collected during the February–April 2025 DEPM survey. The annual estimates of spawning biomass were also updated using this new value of $P_0$ (Figure 4–5). In 1995, prior to the two mass mortality events, spawning biomass was approximately 332,000 t. Spawning biomass fell to 87,000 t in 1996 and 76,000 t in 1999 following the events but recovered rapidly to 188,000 t in 2000 and then 268,000 t in 2009 (Figure 4–5). The relatively low estimate of spawning biomass in 2013 largely reflects the incomplete coverage of the spawning area in that year. Since the adaptive approach to sampling was adopted in 2014, estimates of spawning biomass have been above 230,000 t. Prior to 2025, spawning biomass peaked in 2020 at approximately 401,000 t and estimates have been greater than 290,000 t since then. The estimate of spawning biomass for 2024 was 291,731 (248,230–335,232) (Grammer et al. 2024a). During February–April 2025, spawning biomass was estimated to be 556,957 t (474,724–639,191 t), which is the highest estimated biomass in the time series (Figure 4–5; Ivey et al. 2025). The estimate for 2025 calculated using the value of *A* without the stations added since 2020 was 507,002 t (Ivey et al. 2025).

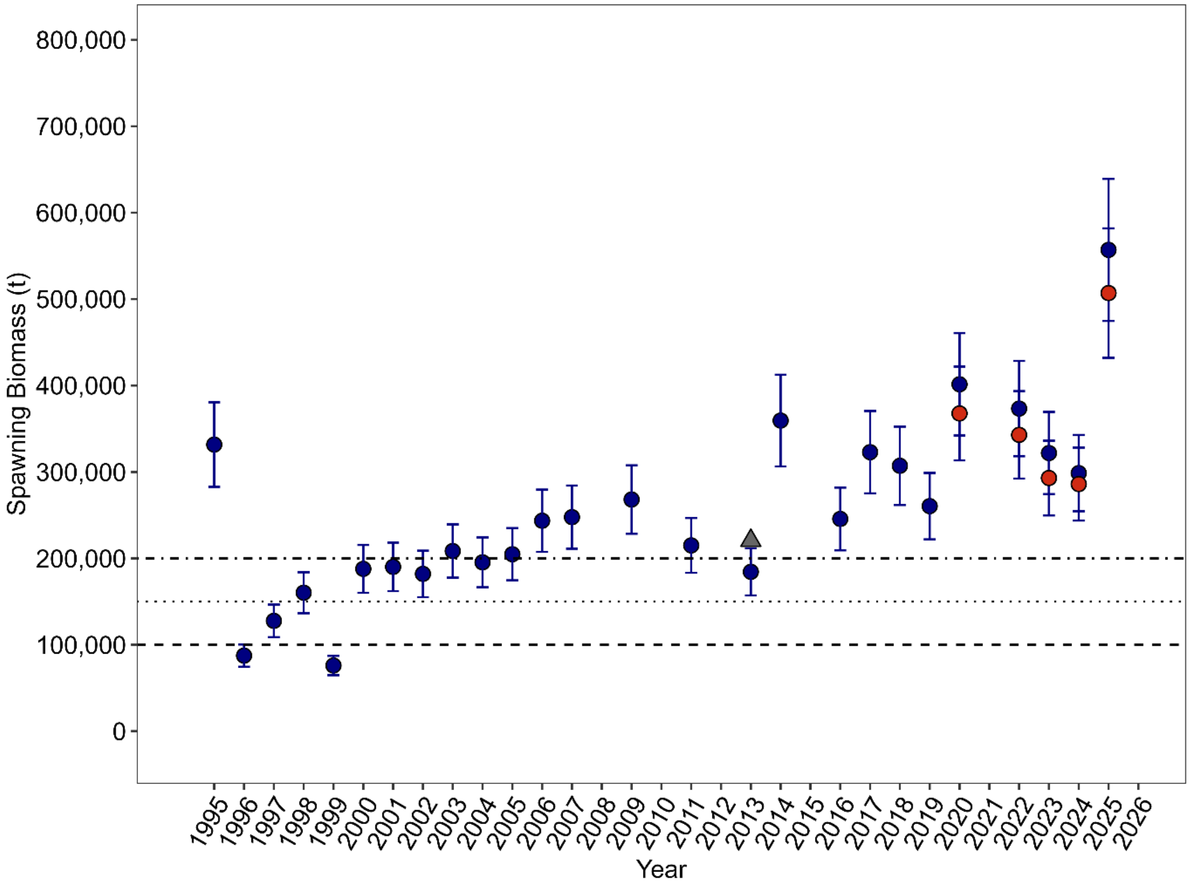


**Figure 4-5.** Estimates of spawning biomass (95% CI) for Sardine off South Australia from 1995 to 2025 using the Daily Egg Production Method (DEPM). Adult parameters were estimated from data obtained during 1998-2024 (Grammer et al. 2024a). Spawning area (*A*) was estimated annually. The log-linear model was used to estimate mean daily egg production ($P_0$) from data collected between 1998 and 2025. The red circles for 2020–2025 are the estimate of spawning biomass obtained using estimate of *A* without the additional stations added since 2020. The triangle for 2013 (when the survey did not cover the entire spawning area) is the estimate of spawning biomass using the mean *A* from 2002 to 2011 (45,406 km$^2$). The horizontal lines indicate the 100,000 t (dash), 150,000 t (dotted) and 200,000 t (dash/dot) reference points in the harvest strategy (PIRSA 2023).

## 4.4 Discussion

The DEPM has been integral to the rapid and sustainable development of the SASF. The information about the size of spawning stock of Australian Sardine in waters off South Australia provided by the DEPM has underpinned the growth of the fishery. Estimates of spawning biomass obtained during the first few years when the method was applied off South Australia were uncertain, due to limited understanding of key parameters, especially mean daily egg production ($P_0$) and spawning fraction (*S*) (e.g. Ward et al. 2001a, 2011). Improved knowledge obtained over the last two decades provided a valuable opportunity to re-evaluate how the size of the population has fluctuated over time and develop recommendations about how the method should be applied (see Ward et al. 2021). Those recommendations have been implemented since 2020 to ensure that future estimates of spawning biomass are as accurate and precise as possible (e.g. Grammer et al. 2021, Grammer and Ivey 2022, 2023, Grammer et al. 2024a, Ivey et al. 2025)

The revised estimate of spawning biomass for 1995 of approximately 332,000 t provides a useful proxy for unfished spawning biomass (see Chapter 5). Similarly, the estimates of spawning biomass of 87,000 t in 1996 t and 76,000 t in 1999, provide useful insights into the likely impacts of the two mass mortality events on the adult population. The increase in the spawning biomass from 6,000 t in 1999 to 268,000 t in 2009, shows how quickly the population recovered from the two mortality events. The low estimate of spawning biomass in 2013 largely reflects the failure of that year's survey to cover the entire spawning area. Since the adaptive approach to sampling was adopted in 2014, estimates of spawning biomass have been consistently above 230,000 t. Spawning biomass increased in 2020 to approximately 401,000 t and estimates have been greater than 290,000 t since then. In 2024, spawning biomass was estimated to be 291,731 (248,230–335,232) t, which is comparable to estimates since 2014, however there was an intense and sustained upwelling event that year, which appeared to limit the available spawning area, potentially concentrating Sardine into the remaining favourable spawning habitat (Grammer et al. 2024a). In contrast, spawning during February–April 2025 was widespread, with high egg densities observed across most of survey area (Ivey et al. 2025). This resulted in the largest spawning area and the highest spawning biomass on record of 556,967 (474,724–639,191) t in 2025 (Ivey et al. 2025).

Previous studies have shown that Sardine abundance is strongly correlated with spawning area (Mangel and Smith 1990, Gaughan et al. 2004). Spawning area has been confirmed as a good proxy for the abundance of adult Sardine off South Australia (Ward et al. 2021). Using historical data to estimate all DEPM parameters except spawning area means that fluctuations in estimates of spawning biomass are driven entirely by changes in the measure of spawning area. As a result, future surveys must cover as much of the spawning area as possible and should continue to involve the adaptive approach to sampling that has been in place from 2014 onwards. The total area surveyed in 2025 of 140,900 km$^2$ was the largest to date. The estimate of spawning area in 2025 of 114,600 km$^2$ was also the highest on record. The large spawning area observed in 2025 provides strong evidence that Sardines were widespread and abundant off South Australia during February–April 2025.

Inter-annual variability in estimates of $P_0$ is low compared to statistical uncertainty (imprecision) for Sardine off South Australia (e.g. Ward et al. 2020b, 2021). The estimate of $P_0$ obtained by adding data from each additional DEPM survey (e.g. 2025) to all historical data was more precise (SD = 4.3) than the estimate obtained using data from a given year only (e.g. 2025: SD = 17.4). Using historical data to estimate $P_0$ prevents large inter-annual fluctuations in estimates of spawning biomass driven by variations in the annual estimates of this parameter caused by statistical uncertainty. However, it is critical that $P_0$ continue to be monitored annually to look for changes in the parameter over time to reduce the risk of over- or under-estimating spawning biomass, e.g. the basin hypothesis of McCall 1990 (Ward et al. 2021). In future applications of the DEPM to Sardine off South Australia, $P_0$ should continue to be estimated using data obtained in all years since 1998, as well as within each year.

Adult reproductive parameters for Sardine off South Australia were not correlated with spawning area, and correlation would have suggested that density dependent effects had occurred (Ward et al. 2021). Detecting changes in the adult population of Sardine over time due to environmental conditions or density dependent effects is important. Adult sampling is costly and logistically challenging, yet necessary. The ability to detect changes in key adult parameters of Sardine, such as spawning fraction, is critical, since errors when estimating these parameters have major implications for estimates of spawning biomass (see Ward et al. 2021). An extensive adult sampling program was conducted in 2024 and strengthened our understanding of key adult reproductive parameters. This program should continue to be repeated every 5 years to determine if changes to adult parameters have occurred.

Estimates of adult parameters from samples obtained in 2024 were within the range of the annual estimates from previous years. Re-analysis of all adult samples of Sardine collected off South Australia since 1998, including 2024, produced values that were similar to the all-years values for each parameter reported in Ward et al. (2021) (Grammer et al. 2024a). This indicates that both individual parameters and mean daily fecundity have been relatively stable among years, especially when inter-annual variability is evaluated within the context of potential sources of statistical uncertainty (i.e. precision and bias; Ward et al. 2021). Large variations of the estimates of adult parameters among years are likely indicative of the limitations of adult sampling, rather than actual differences among years in the reproductive patterns of the population (Ward et al. 2021). Therefore, in the foreseeable future, adult parameters used to calculate the spawning biomass of Sardine off South Australia should continue to be estimated from data obtained in all adult surveys since 1998.

# 5. STOCK ASSESSMENT MODEL

## 5.1 Introduction

This chapter describes the application of the stock assessment model, SardEst, developed specifically for the SASF (Ward et al. 2020b). In 2019, this model superseded the Stock Synthesis model (the SS model) used in previous assessments (Ward et al. 2015, 2017, 2020a).

SardEst is based on a single stock, single fleet and single area, and fits to commercial catch data (Chapter 2), fishery-dependent age-composition data (Chapter 3) and fishery-independent estimates of spawning biomass obtained using the DEPM (Chapter 4). Biological parameters (e.g. growth, maturity and weight-at-age) are estimated externally from fishery-dependent and fishery-independent data (Chapter 3). Model specifications are detailed in Appendix B.

The SardEst model presents three distinct features compared to other models previously used: 1) it estimates recruitment of fish at age one, as deviations to an average value ($\bar{R}$) that are fit as random effects, 2) natural mortality (*M*) is freely estimated as a time and age invariant parameter rather than being assumed, and 3) the mass mortality events of 1995 and 1998 are explicitly estimated using increased natural mortality (*M*) in those years. SardEst is built in Template Model Builder (TMB), which is a contemporary, auto-differentiation program that incorporates random effects (Kristensen et al. 2016). This approach provides better estimates of recruitment deviations compared to models previously used. Recruitment deviations are explicitly treated as random annual processes that fluctuate around the mean recruitment $\bar{R}$ (Thorson et al. 2014). Improved estimates of recruitment are important as they ensure the model provides better estimates of annual fishing mortality (*F*) and natural mortality in 1995 and 1998, when the mass mortality events occurred (Ward et al. 2001b).

The 2019 SardEst model version (Ward et al. 2020b) was externally reviewed by CSIRO in 2020 (Hillary 2020). The review indicated that SardEst was a clear improvement on the previous SS model (Ward et al. 2015, 2017, 2020b), but made a series of recommendations to continue model improvement: 1) clarify whether selectivity is being fixed or estimated; 2) correct a misspecification of the catch-at-age likelihood; and 3) apply data weightings consistent with agreed best practice. Implementation of these recommendations began in 2021 and continued in the previous stock assessment (Grammer et al. 2024b, Appendices B and C). During implementation of these recommendations, a coding error was introduced, which was detected and corrected in the application of the SardEst model for the previous assessment (Grammer et al. 2024b). The corrected version of the SardEst model has been used in this assessment.

## 5.2 Methods

### 5.2.1 Base-case model

*Model structure*

The SardEst model is age-structured and sex-independent and assumes a single area fleet and stock for the SASF. The 2025 model includes data from the commencement of the fishery to present (1992 to 2025 by calendar year). Annual age-composition data were available from 1995–2024, except for 2007. Therefore, predicted catch-at-age in 2007 are not fitted to data. Annual spawning biomass estimates are available from 1995 to 2025 but are not available for 2008, 2010, 2012, 2015 and 2021 when DEPM surveys were not undertaken. Therefore, spawning biomass is not fitted to data in those years. As SardEst is a single sex model, spawning biomass includes both males and females. The model time step is annual.

SardEst uses the Hybrid *F* method to estimate fishing mortality (*F*) which is also implemented by Stock Synthesis (Methot 2000). It is called 'hybrid' as it combines the best features of the standard Pope-approximation catch-conditioned models and effort-conditioned Baranov models. It assumes exponential survival within each time step of Baranov, but rather than setting *F* proportional to fishing effort, it computes the Baranov *F* that is needed to remove the exact reported catch across each model time step. The survival of Sardine in each age class is then adjusted with these estimates of *F* and fitted to fishery age-composition data and DEPM estimates of spawning biomass. The advantage of this approach is that it reduces the number of parameters estimated by the model (no catchability is defined), while giving exact reported catch removals (Methot 2000).

*Biological and fishery parameters*

The biological parameters (i.e. growth and maturity) used in the models were based on information presented in previous chapters. Previous analyses found no significant temporal changes to these parameters during the history of the fishery, or that there had been insufficient sampling to detect inter-annual variations (Ward et al. 2010, 2012, 2015, 2017, 2020a, Grammer et al. 2021, 2024b). Each parameter was fixed at historical values and held constant in the stock assessment model.

Growth was assumed to follow the von Bertalanffy growth function with sex-independent parameters (Table 5-1). Sex specific weight-length relationships were derived from both commercial and fishery-independent samples. An allometric relationship of the form $W = A * FL^B$

was applied, where *W* is weight in kg, *FL* is caudal fork length in mm and *A* and *B* are the scaling and power coefficients, respectively.

Maturity-at-age was determined for females using a logistic regression fit with a binomial error structure and a logit-link function where the logistic function takes the form:

$$P(a) = \left(1 + e^{-\ln(19)\left(\frac{a-a_{50}}{a_{95}-a_{50}}\right)}\right)^{-1}$$

Where *P(a)* is the proportion mature-at-age *a,* $a_{50}$ is the age at 50% mature and $a_{95}$ is the age at 95% mature. Female $a_{50}$ and $a_{95}$ were estimated as 2.63 years and 4.10 years, respectively (Table 5-1; Figure 5-1).

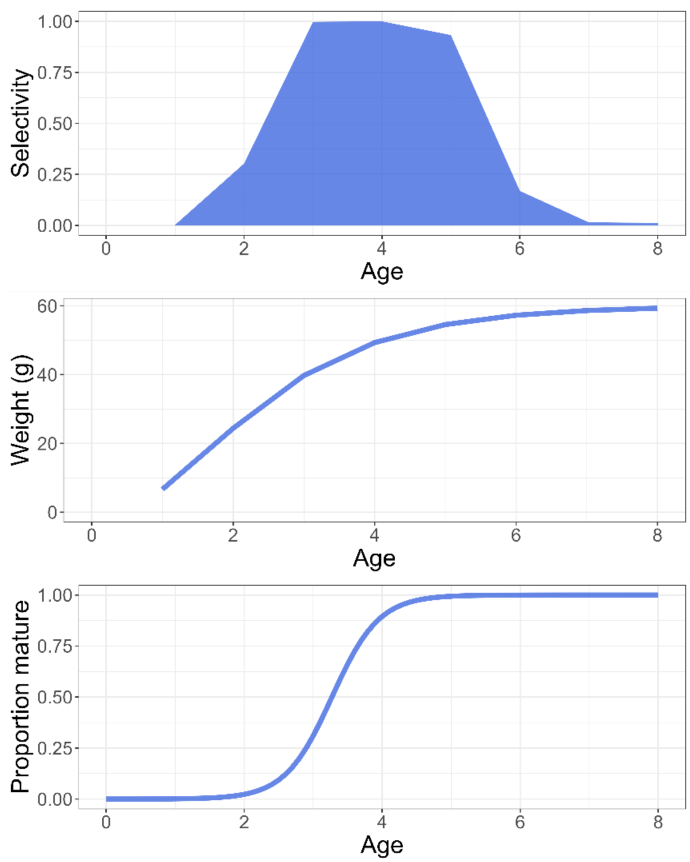


**Figure 5-1.** Age-based selectivity (expected proportion available to fishing by age), weight (g) and proportion of mature females used as inputs to SardEst.

The SardEst model assumes that fishing occurs across a single stock and single area. In the SS model (prior to SardEst; Ward et al. 2015, 2017, 2020b), selectivity for the commercial fishing fleet was assumed to be a time-invariant, dome-shaped function of age, with the parameters of a double-normal selectivity curve being estimated in the model (Methot 2000). The estimation of parameters in the double-normal curve in SardEst was more difficult because of the lack of precision and consistency in length-, weight-, and age-frequency data. Consequently, the selectivity parameters estimated in Stock Synthesis have been used as fixed parameters in SardEst since 2019 (Figure 5-1) (Ward et al. 2020b, Grammer et al 2021, 2024b). These parameters result in a selectivity curve with a descending right-side limb that mimics the expected reduced availability of older fish to the main components of the fishery, where younger (and smaller) fish dominate (Figure 5-1).

*Natural mortality and mass mortality events*

Natural mortality (*M*) has been freely estimated in the current SardEst rather than being a fixed at 0.7yr$^{-1}$, as was done in previous assessments (Ward et al. 2015, 2017, 2020a). This was facilitated by increased precision in the inputs from the DEPM biomass data (Ward et al. 2021), that allowed natural mortality to be estimated rather than assumed. *M* was estimated as constant for all ages and across all years except for 1995 and 1998. In those years, two mass mortality events each killed an estimated 70% of the adult population (Ward et al. 2001b). Here, the SardEst model estimated the increased natural mortality for the adult population based on declines in spawning biomass as determined through DEPM surveys. Mass mortality was assumed to only affect the mature fish. This was performed by estimating the maximum level of additional mortality ($M_t^{max}$) in year *t* (where *t* = 1995 or 1998) and multiplying this value by the proportion mature at each age class.

For example, natural mortality-at-age *a* in 1995 ($M_{1995}^{max}$) was estimated as:

$$M_{1995,a} = M + M_{1995}^{max} * P(a)$$

Where *P(a)* is the proportion mature-at-age *a*. Total mortality-at-age ($Z_{t,a}$) is then the sum of total natural mortality-at-age and fishing mortality-at-age *a* ($F_{t,a}$) determined via the hybrid method:

$$Z_{1995,a} = M_{1995,a} + F_{1995,a}$$

*Model parameters and likelihood weighting*

The SardEst model fits to two data sources as likelihood components: 1) Annual age-compositions (1995–2006 and 2008–2024), and 2) DEPM spawning biomass estimates (1995–2007, 2009, 2011, 2013, 2014, 2016–2020, 2022-2025). Additionally, annual total catches are used to condition estimates of *F* during the Hybrid *F* tuning method (Methot 2000). The likelihood components include the fits to age compositions and DEPM estimates, as well as the log-recruitment deviates, which are fitted as random effects. The estimated parameters of SardEst are:

1. $\bar{R}$ – mean number of recruits in log space.
2. $\tilde{R}_t$ – recruitment deviations for year *t* in log space
3. $\sigma_R$ – the standard deviation of the recruitment deviates in log space
4. $M$ – natural mortality as time and age invariant
5. $M_t^{max}$– the maximum level of additional mortality in year *t* (where *t* = 1995 or 1998).

Based on the recommendations of the SardEst review (Hillary 2020), the likelihood function used for the age-compositions was modified to incorporate annual sample sizes. In the 2021 stock assessment (Grammer et al. 2021), the total number of fish per catch sample per year (n) was used as the effective sample size. In the 2023 assessment, this was changed to the number of catch samples (N) per year, while the data weighting for the age-compositions also needed to be adjusted due to this modification (see below and Appendix C). This approach was retained in the current assessment.

During model estimation, TMB first maximises the likelihood for the random effects (recruitment deviates) for a proposed set of fixed effects. Following this, TMB calculates the Hessian matrix for these random effects and uses this to compute the joint likelihood of both random and fixed effects (Thorson et al. 2015). Due to random effects being estimated prior to the fixed effects, it was apparent that the model was initially maximising the joint likelihood at lower estimates of $\sigma_R$. Therefore, data weighting needed to be applied. In the 2023 assessment, likelihood weightings were adjusted to reflect the relative precision of the data sources. DEPM estimates, which have become more reliable due to increased precision (Ward et al. 2021), were given a likelihood weighting of 1.0. In contrast, the weighting for age-composition data was reduced to 0.2. This adjustment means that the influence of the age-composition likelihood was reduced by a factor of five relative to the DEPM biomass likelihood. The same likelihood weightings were applied in the current assessment.

### 5.2.2 Input data

Data from multiple sources were integrated for the purposes of the assessment, including age-composition data, spawning stock biomass estimates from DEPM surveys (Chapter 4), and catch data from the commercial fishery. Table 5–1 shows the data used in the model by type, year, and data source.

**Table 5-1**. Model specifications for the SardEst assessment model.

| Specification | Value |
|---|---|
| **Time-step** | Yearly |
| **Model years** | 1992–2025 |
| **Catch (t)** | 1992–2024 |
| **Spawning biomass (t, yearly, from DEPM)** | 1995–2007; 2009; 2011; 2013–14, 2016–20, 2022-25 |
| **CPUE index** | Not included |
| **Model age classes** | Ages 1–8+ |
| **Age composition data** | Ages 1–8, 1995–2024 (excluding 2007) |
| **Growth parameters** | Fixed, time-invariant von-Bertalanffy |
| K | 0.71 |
| $L_\infty$ | 17.8 |
| $L_0$ | 0.035 |
| **Length-weight relationship (both sexes)** | Fixed power function (approx. cubic) |
| *A (Scalar parameter)* | $5.03*10^{-6}$ |
| *B (Power parameter)* | 3.26 |
| **Maturity (females only)** | Fixed logistic function of age |
| $A_{50}$ | 2.63 years |
| $A_{95}$ | 4.10 years |
| **Stock-recruitment** | Estimated Average recruitment ($\bar{R}$) |
| Recruitment deviations | Estimated as random effects |
| Recruitment variance, $\sigma_R$ | Estimated |
| **Selectivity** | |
| Commercial Fishery | Fixed, domed-shaped function of age |

*Commercial catch data*

Commercial catch data were available for all years between 1992 and 2024. Data based on CDRs were used, as they are considered most accurate. Full details on the collection and analyses of commercial catch data are presented in Chapter 2. As only partial catch data was available for 2025, an assumption was made that the 2025 total catch would match the allocated TACC for 2025 of 50,000 t. The same approach was taken in the previous stock assessment (Grammer et al. 2024b).

*Fishery-independent spawning biomass estimates*

Spawning biomass estimates obtained from annual DEPM surveys from 1995–2007, 2009, 2011, 2013, 2014, 2016–2020, 2022-2025 were used as a measure of absolute abundance in the model. The methodology for estimating daily egg production was updated in Chapter 4 of this assessment so that consistent methodology was applied across the time series of surveys. These refined estimates of spawning biomass and their coefficients of variation were included in the SardEst model.

*Age data*

Age composition data from commercial catches were available for all years between 1995 and 2024, except for 2007. Ages were determined from an estimated otolith-weight~age relationship and applied to individuals from commercial catch samples for which an otolith weight was available. Details on the collection of age-composition data and determination of age from otolith weights are presented in Chapter 3.

### 5.2.1 Sensitivity analyses and model diagnostics

The sensitivity of the assessment model changes in two quantities: 1) age-at-recruitment which is a fixed value, and 2) *M* which was previously fixed (Ward et al. 2020b) but is now estimated (see Grammer et al. 2021). This was achieved for age-at-recruitment by re-fitting the model across a greater range of values. The impact of different age-at-recruitment values on spawning biomass was also examined. The impact of a fixed *M* versus an estimated *M* was examined by re-fitting the model using multiple fixed *M* values and determining their impact on estimates of spawning biomass and harvest fraction.

## 5.3 Results

### 5.3.1 Model fits to data

Model estimates of spawning biomass align with those derived using the DEPM, including during the mass mortality years (1995 and 1998) (Figure 5-2), which had been overestimated in previous models (Ward et al. 2017). An exception occurred around 2014, when DEPM estimates increased sharply from 2013 before declining again in 2016, whereas the model effectively smoothed this variability. In 2025, the model estimate was approximately 80,000 t lower than the DEPM estimate, reflecting an unprecedented increase in the DEPM estimate between 2024 and 2025, and lack of age-composition data for 2025. Standard deviations of SardEst spawning biomass estimates were generally lower than those from the DEPM, indicating overall consistency among data sources (catch, DEPM, and age composition). SardEst also provided good fits to age-composition data across most years of the fishery (Figure 5-3), with poorer fits following the 1995 and 1998 mass mortality events. Overall, the model fits to age-composition data were satisfactory.

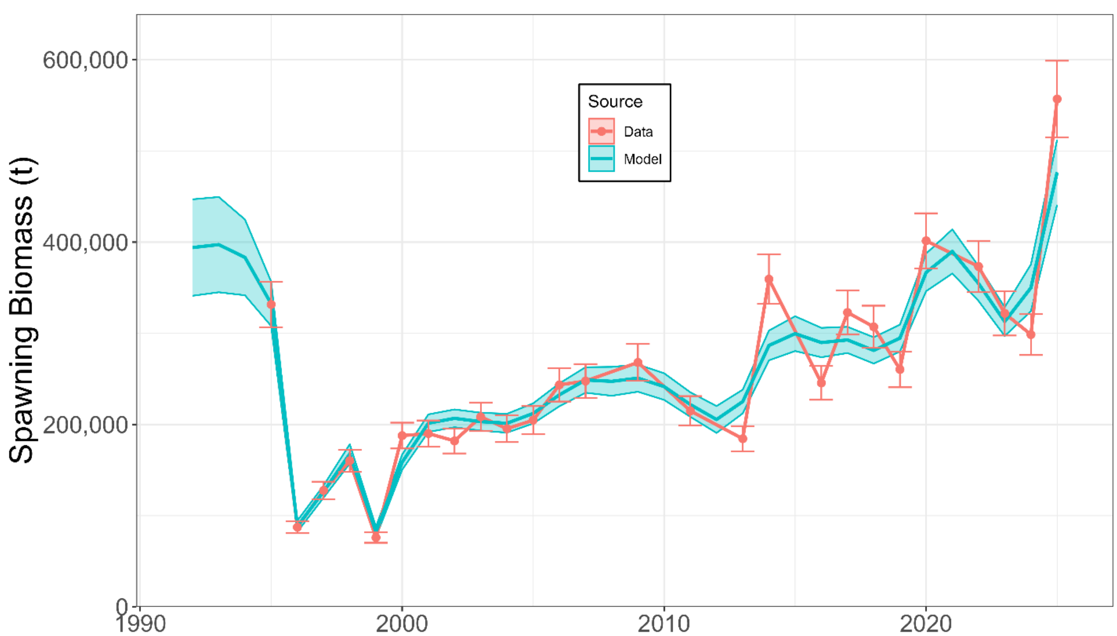


**Figure 5-2.** Estimated spawning biomass (total weight of mature fish) from the SardEst model. Blue line and shading represent the annual model estimates and respective standard deviations. Red points and lines show annual estimates of spawning biomass from DEPM surveys. Red error bars are the standard deviation of these survey estimates. Note that surveys did not occur in 2008, 2010, 2012, 2015 and 2021.

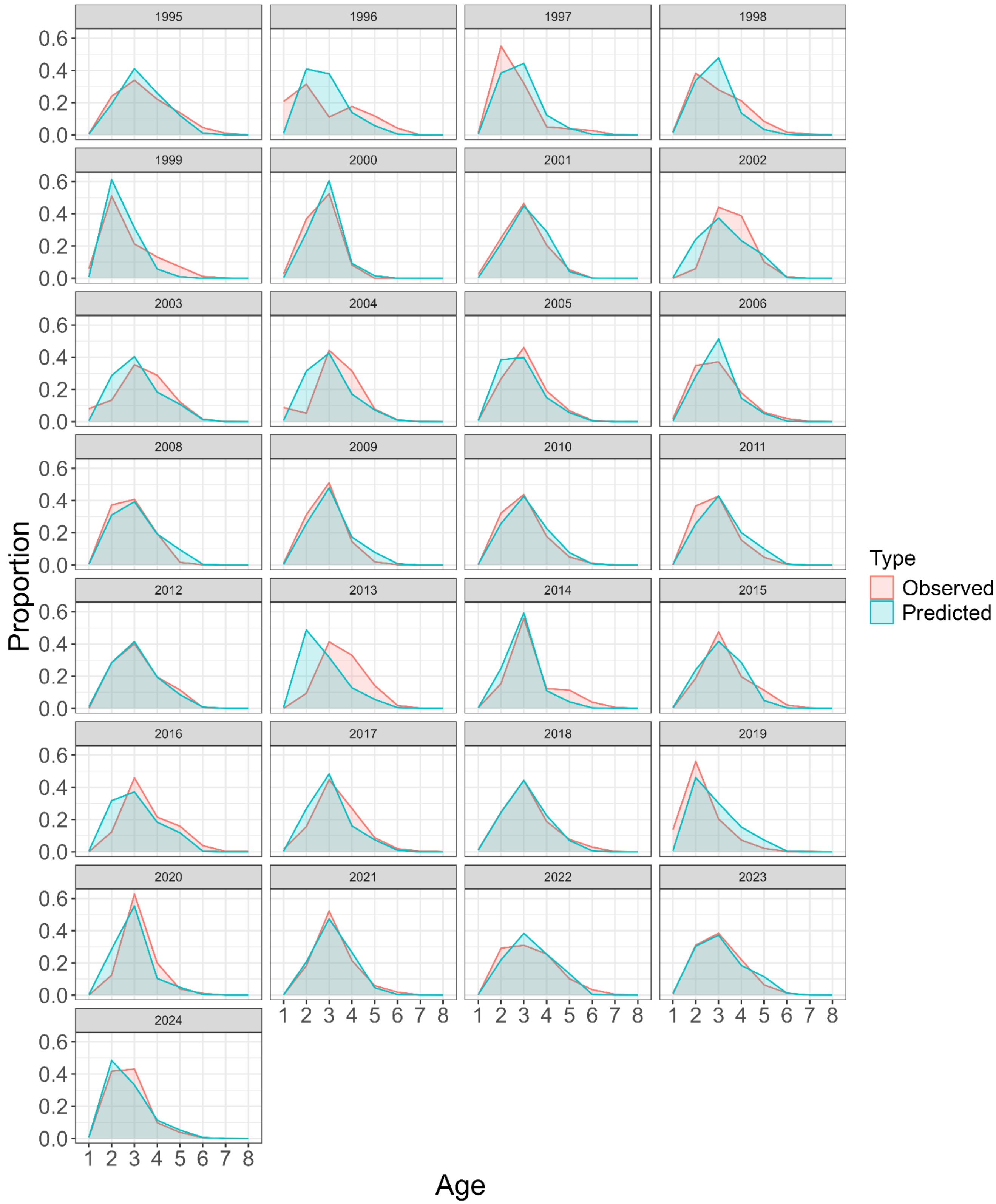


**Figure 5-3.** Comparison of annual observed (red shading) and model estimated (blue shading) age compositions. Note: no age compositions were available in 2007.

### 5.3.2 Parameter estimates

The two fixed effects recruitment parameters ( $\log(\bar{R})$ and *log(σR)*) were estimated with high levels of precision (Table 5–2), while estimates of $M_{1995}^{max}$ and $M_{1998}^{max}$ were less precise. This was anticipated given that estimating natural mortality in integrated stock assessment models is a difficult undertaking (Sippel et al. 2017). The annual recruitment deviates (random effect parameters in log space) were estimated between -0.71 and 1.03.

**Table 5-2**. Fixed effects parameters with standard deviation estimated by SardEst.

| Parameter | Estimate | Standard Deviation |
|---|---|---|
| $\log(\bar{R})$ | 16.36 | 0.15 |
| $log(\sigma_R)$ | -0.80 | 0.12 |
| $M_{1995}^{max}$ | 1.99 | 0.31 |
| $M_{1998}^{max}$ | 2.73 | 0.64 |
| $M$ | 0.66 | 0.05 |

### 5.3.3 Biomass and relative depletion

SardEst modelled total biomass ($B_0$) in 1992 was 723,000 t (± 110,000 t) (Figure 5-4). The lowest level of total biomass in the history of the fishery was 244,000 t (± 18,000 t) in 1996, the year following the first mass mortality event. This represents the lowest level of depletion at 33% (± 5%) (Figure 5-4). Since 2000, the fishery has recovered and consistently remained above 50% depletion. The mean level of depletion over the history of the fishery has been 75% (± 11%) and in 2024, the estimated depletion was over 130%. This corresponds to a total biomass of 961,000 t (± 121,000 t). In 2025, the estimated depletion was 142% for a total biomass of 1,025,000 t (± 318,000 t). The standard deviations of the SardEst estimates of total biomass and depletion for 2025 were considerably higher than those for other years.

Model estimated spawning biomass in 2024 was 350,000 t (± 26,000 t) (Figure 5–2), which is more than twice the upper trigger reference point of 150,000 t set in the Management Plan (PIRSA 2023). The model estimate for 2025 was 477,000 t (± 36,000 t). The spawning biomass has only fallen below the upper trigger reference point of 150,000 t in the years immediately after the mass mortality events of 1995 and 1998 (Figure 5–2).

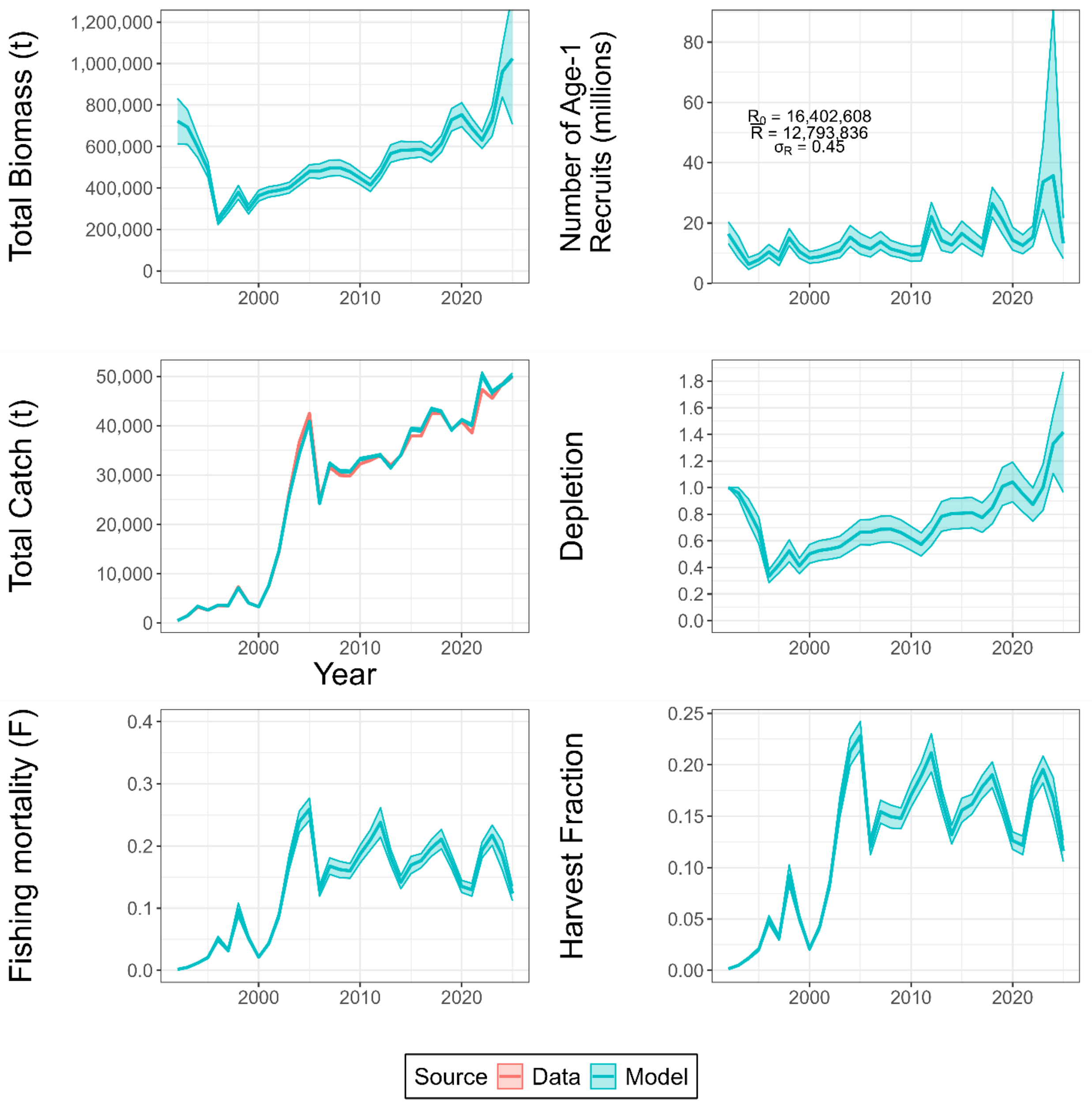


**Figure 5-4.** Estimates and standard deviation of time series derived quantities from SardEst. These include (left to right and top to bottom): 1) Total biomass (total weight of all age 1+ fish); 2) Annual recruitment (number of age 1 fish); 3) Annual total catch; 4) Level of depletion (Total biomass in 1992 [$B_0$] divided by annual total biomass); 5) Full, annual, instantaneous, fishing mortality (*F*); and 6) Harvest fraction (*H*). Blue lines denote model estimated values and blue shading represents the standard error around each estimate. Observed annual catches are represented by the red line.

### 5.3.4 Mass mortality events of 1995 and 1998

SardEst estimated that ages 5 years and older had an *M* of 2.85 $yr^{-1}$ in 1995 and 3.48 $yr^{-1}$ in 1998. Mass mortality was assumed to be less for Sardine aged 4 and under (Figure 5–5), for which the maximum level of additional mortality ($M_t^{max}$) was assumed to be reduced by the independent estimates of proportion-mature-at-age. These estimates of mortality enabled significantly closer model fits to DEPM spawning biomass estimates in 1995 and 1998 than other stock assessment models (e.g. the SS Model) (Ward et al. 2020b). Earlier estimates of mortality rates in the mass mortality events of 1995 and 1998 were around 70% adult mortality across mature age classes (Ward et al. 2001b).

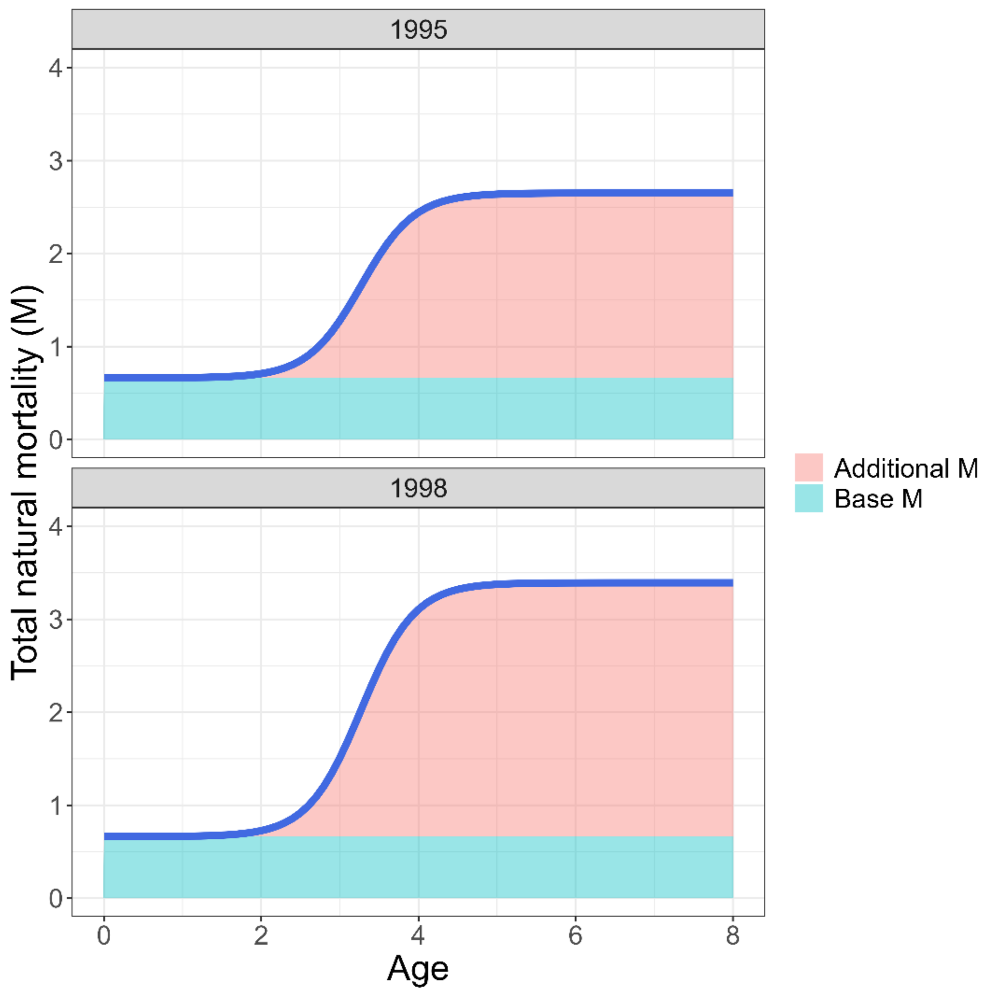


**Figure 5-5.** Natural mortality-at-age ($M_a$) during the 1995 and 1998 mass mortality events. The blue line indicates the total level of *M* for each age class. The blue shading shows the estimated and fixed level of *M* applied to all ages and years in the model. The red shading shows the additional $M_a$ estimated by the SardEst model in 1995 and 1998.

### 5.3.5 Recruitment

Model estimated recruitment ($R_0$) in 1992 was 16.4 million age-one fish (± 1.3 million). The model-estimated mean recruitment ($\bar{R}$) was 12.8 million which differed from $R_0$ by approximately 20%. Recruitment mostly remained between 10 and 25 million recruits (Figure 5-4) with two main peaks of 22 million and 26 million recruits in 2012 and 2018, respectively. The model estimated 2012 and 2018 to be the years of high recruitment as 2014 and 2020 had a high biomass (Figure 5–4) and was composed mostly of age three fish (Figure 5–3). The model also estimated high recruitment in 2023 and 2024. The standard deviations around these two estimates were higher than those in other years.

### 5.3.6 Exploitation rates

The Hybrid *F* method provided nearly exact agreement with the yearly catch totals in weight, therefore yielding more accurate estimates of annual fishing mortality (*F*). Since 2010, the highest levels of *F* (0.24 $yr^{-1}$, ± 0.02) occurred in 2012, with other high levels (0.21 $yr^{-1}$, ± 0.02)) in 2018 and 2023. The increase in 2012 was due to a decline in model-estimated biomass, while the increase in 2018 and 2023 was due to both a decline in model-estimated biomass and an increase in catch (Figure 5–4). Another high level of *F* (0.26 $yr^{-1}$, ± 0.02) occurred in 2005, although this increase in *F* was due to an increase in catch (Figure 5–4). Over the last 10 years, *F* has remained between 0.13 and 0.24 $yr^{-1}$, with a significant decrease in the last 3 years due to an increase in the total biomass. The level of *F* in 2024 was 0.18 $yr^{-1}$ (± 0.02) which equates to a harvest fraction of 17.0% (± 2.0%). The level of *F* in 2025 was 0.12 $yr^{-1}$ (± 0.01) with a harvest fraction of 12.0% (± 1.0%) the lowest it has been since 2002.

### 5.3.7 Model diagnostics

One key input is a fixed parameter in the SardEst model: the age-at-recruitment. Sensitivity analyses performed using different values of this parameter demonstrated that the age-at-recruitment could have an effect on model spawning biomass (Figure 5–6). However, an age-at-recruitment from zero to two years had little effect on the spawning biomass estimates, with the exception of years 1992–1994, where estimates of spawning biomass to inform the model are not available (Figure 5–6). The rest of the spawning biomass time series mainly differed when age-at-recruitment was three (Figure 5-6). This is an unrealistic age-at-recruitment as individuals aged one and two years are regularly present in age samples (Figure 5–3; Chapter 3). Therefore, this difference can be disregarded.

Sensitivity analyses performed using different values of natural mortality demonstrated that estimating the value of natural mortality in the model had little effect on key outputs of the model, the spawning biomass and the harvest fraction (Figure 5–7).

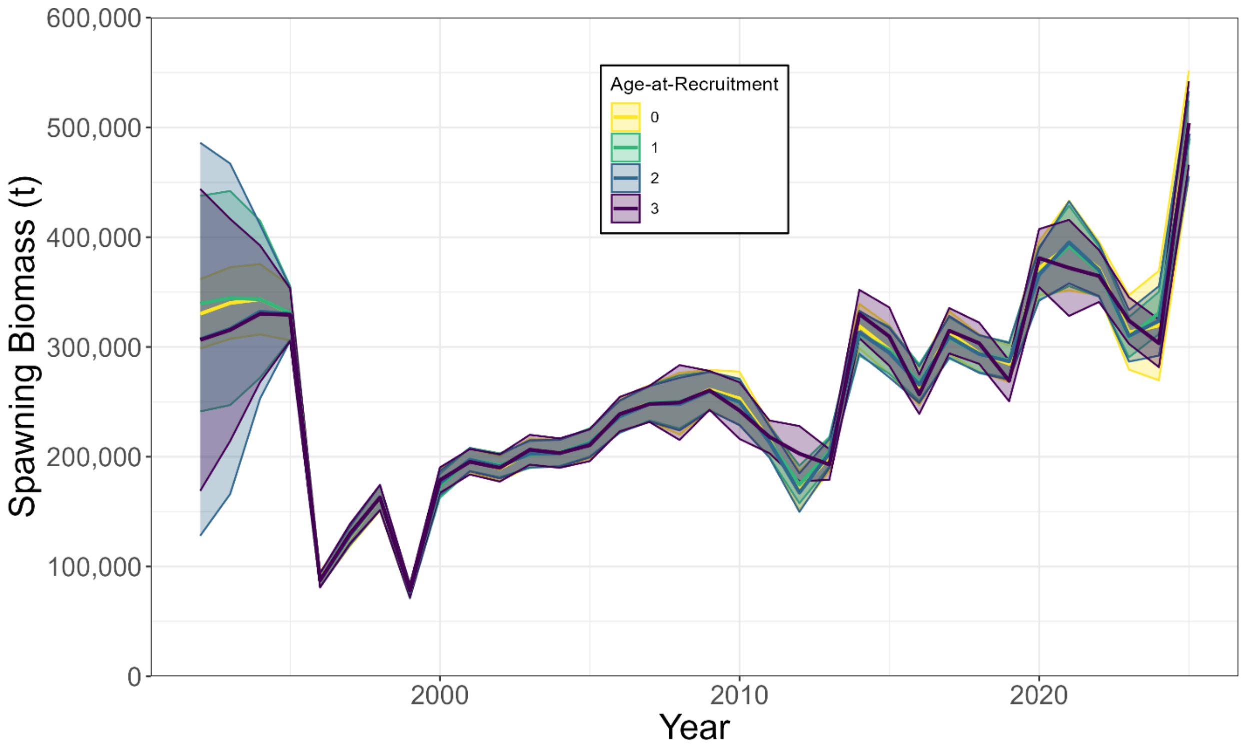


**Figure 5-6.** Model sensitivities to fixed values of age-at-recruitment. The figure shows different model estimates of spawning biomass using different values of the parameter in the model. Lines are the model estimates and shaded areas are the standard deviations.

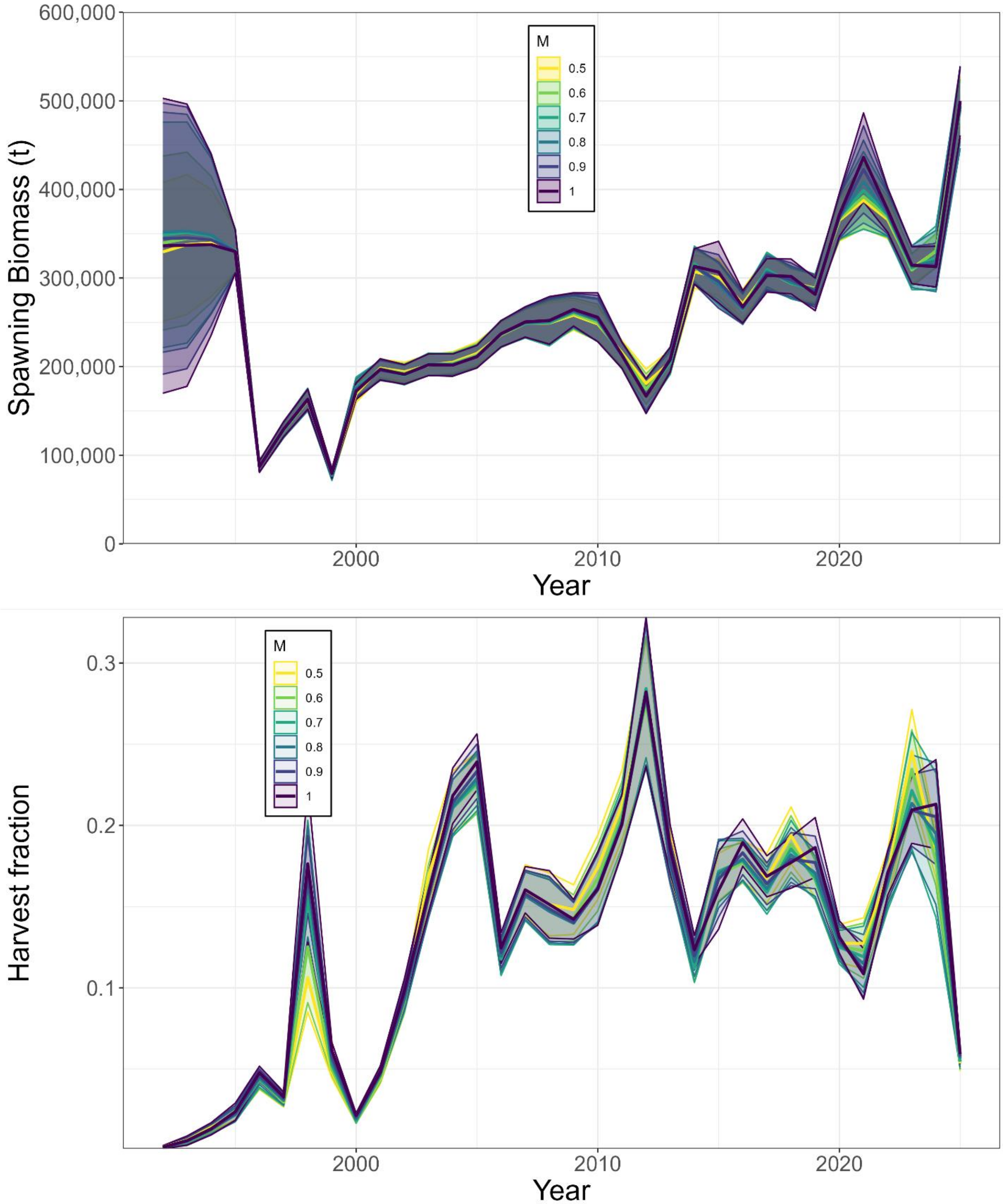


**Figure 5-7.** Model sensitivities to different values of natural mortality. Top panel shows different model estimates of spawning biomass using different values of natural mortality in the model. Bottom plot shows different model estimates of harvest fraction using different values of natural mortality in the model. Lines are the model estimates and shaded areas are standard deviations.

## 5.4 Discussion

The SardEst model was refined in 2021 following methodological updates that led to more precise DEPM-based estimates of spawning biomass (Ward et al. 2021). A key development in that assessment was the incorporation of methods to estimate natural mortality (M) directly (Grammer et al. 2021). While estimating M in integrated stock assessment models has long been discussed, it has rarely been achieved with confidence (Brodziak et al. 2011). Simulation studies suggest that M can be estimated when models are correctly specified (Lee et al. 2011; Sippel et al. 2017), but since all stock assessment models have some degree of misspecification, accurate estimation of M remains challenging (Francis 2012). Attempts to estimate time-varying M can also introduce instability and affect results across the time series (Johnson et al. 2015). As such, estimating M continues to be a contentious issue in stock assessment modelling (Francis 2012; Johnson et al. 2015).

Since 2021, improvements in spawning biomass estimates have enabled SardEst to estimate a time- and age-invariant M (Ward et al. 2021; Grammer et al. 2024a; Ivey et al. 2025). These improved estimates enhanced understanding of the population's survivorship, enabling M to be estimated rather than fixed at an assumed value. In the current assessment, the estimate of M was estimated at 0.66 $yr^{-1}$, which is consistent with the fixed values (0.6 $yr^{-1}$ and 0.7 $yr^{-1}$) used in earlier assessments (Ward et al. 2017; 2020b). Recent assessments (Grammer et al. 2021, 2024b), show that estimating M has not affected key management quantities such as spawning biomass and harvest fraction. Therefore, continuing to estimate M within SardEst is considered appropriate, as it does not alter the conclusions or management advice derived from the model.

Data weighting can have substantial impact on the outcomes of integrated stock assessment model outputs (Francis 2011; 2017). The data weightings applied to the DEPM biomass likelihood and annual age-composition likelihood for the 2023 stock assessment were adjusted due to: 1) the modification of the likelihood function used for the age-compositions to incorporate the effective annual sample sizes (*N* rather than *n*) (Hillary 2020; Appendix B), and 2) correction of the coding error found in the 2021 SardEst model (Grammer et al. 2024b). In line with the weighting approach proposed by Francis (2011), which recommends that models should approximately fit the trends in abundance indices and the variation implied by the residuals around the estimates should match the variation assigned to those data, the DEPM biomass likelihood was assigned a weight of 1.0, while the age-composition likelihood was down-weighted to 0.2. These weightings reflect the higher precision in DEPM data (Ward et al. 2021, Grammer and Ivey 2023) compared to age composition data. The same data weighting values were applied in the current stock assessment and produced a reasonable model fit and variance around the spawning biomass estimates.

Overall, and as expected given the model inputs, SardEst estimates of spawning biomass closely aligned with those derived using the DEPM. An exception occurred in 2025, when the SardEst estimate of 477,000 t (± 36,000 t) was approximately 14% lower than the DEPM estimate of 556,967 t (474,724–639,191 t; Ivey et al. 2025). This difference largely reflects the simplified modelling approach used to maximise the likelihood components. SardEst assigned a low probability to the possibility that the substantial increase in DEPM-estimated spawning biomass between 2024 and 2025 was driven by an abrupt recruitment pulse. As a result, and to maximise the likelihood, the model applied a stronger penalty to recruitment deviations from the mean in 2025, which in turn produced a smoother spawning biomass trajectory. Despite this discrepancy, both DEPM and SardEst estimates remained well above the target reference point of 200,000 t specified in the Management Plan (PIRSA 2023).

The increase in the DEPM-derived estimates of spawning biomass over the past two years has contributed to higher total biomass estimates from SardEst. In 2024, SardEst modelled total biomass was 960,000 t (±121,000 t), rising to 1,024,000 t (±317,000 t) in 2025. Both estimates exceed the biomass ($B_0$) estimate of 723,000 t (±109,000 t) for 1992 (i.e., at the start of the model time series), corresponding to relative depletion levels of 133% and 142%, respectively. These elevated values suggest that the Sardine population has not only recovered but expanded beyond its estimated level in 1992. However, early biomass estimates, prior to 1995, are less reliable than more recent ones, as DEPM surveys were not conducted until 1995, and earlier surveys are considered less dependable due to the assessment program being in its early stages. While this introduces some uncertainty regarding exact depletion levels relative to unfished biomass, the available evidence indicates the stock is currently healthy and is at high levels exceeding those at the start of the fishery.

Stock assessment models, including SardEst, reconcile changes in biomass through adjustments in either mortality or recruitment. Increases in biomass can therefore arise from reduced mortality or stronger recruitment. In SardEst, recruitment is estimated for age-one fish independently of a stock–recruitment relationship, allowing greater flexibility in the use of age composition data. Recruitment is modelled as a random effect around a mean value, which reduces variability in the estimates (Thorson et al. 2014). Given that fishing mortality has remained relatively stable since 2023 (with catches between 45,000 and 50,000 t), the increases in total biomass in 2024 and 2025 were attributed to strong recruitment events in 2023 and 2024. However, the absence of

2025 age composition data limited SardEst's ability to accurately estimate biomass, depletion, and recruitment for those years, resulting in higher uncertainty in the most recent assessments.

SardEst is a recently developed model with scope for further development. Future improvements that should be considered for SardEst include:

1. Projection Capability: SardEst currently does not support projections. Development of a projection component would be beneficial and could be expanded to include management strategy evaluation (MSE) functionality.
2. Sex Structure: The model is currently single-sex, using maturity data for females only. Developing a two-sex model may provide a more accurate representation of the population dynamics.
3. Spatial Structure: SardEst operates as a single-area model and does not account for the spatial structure of the fishery. Developing a multi-zone model may be beneficial as catch proportions increase outside the SG Zone.
4. Selectivity Estimation: Selectivity is a critical parameter that cannot be known *a priori*. Therefore, selectivity should be estimated in the model rather defined as a fixed parameter.
5. Climate-Enhanced Modelling: Incorporating environmental variables into stock assessments is essential for managing fisheries in the context of climate change (Punt et al. 2021). Including time series of environmental data (e.g. sea temperature) and linking them to key biological parameters (e.g. recruitment, growth) could help assess how these parameters are influenced by the environmental inputs.

# 6. DISCUSSION

## 6.1 Stock status and assessment uncertainties

Under the criteria outlined in the harvest strategy for the SASF (PIRSA 2023), the Southern Australia stock of Australian Sardine in 2024 is classified as **Sustainable**. The estimates of spawning biomass obtained using the DEPM in 2024 was 291,731 (248,230–335,232) t (Grammer et al. 2024a), and during February–April 2025 was 556,957 t (474,724–639,191) t (Ivey et al. 2025), which are above the target reference point of 200,000 t (PIRSA 2023). The SardEst model estimate of spawning biomass for 2025 of 477,000 t (± 36,000 t) was also above the target reference point. The exploitation rate for spawning biomass (DEPM) was 17% in 2024 and 12% in 2025, which are below the maximum rate at Tier 2 of 25% identified in the Management Plan (PIRSA 2023). These findings are consistent with other recent assessments of the status of the southern stock of Sardine which classified the stock as sustainable (e.g. Grammer et al. 2024b, Roelofs et al. 2024).

The strongest piece of empirical evidence indicating that the Southern Australia stock of Australian Sardine should be classified as sustainable is that the spawning area recorded during the February–April 2025 DEPM survey was 115,000 km$^2$ (Ivey et al. 2025), which is the largest on record. It is widely recognised that spawning area (*A*) is strongly correlated with the size of the spawning stock of Sardine (e.g. Mangel and Smith 1990, Gaughan et al. 2004, Ward et al. 2021). Under the refined approach used to apply the DEPM in this report, inter-annual variations in estimates of spawning biomass are driven primarily by fluctuations in the spawning area (Chapter 4). Currently, we do not know the uncertainty around the estimation of *A*.

The developments made to the SardEst model in the previous assessment (Grammer et al., 2024b) were also applied in the current assessment. The likelihood for age composition data continued to incorporate effective annual sample sizes (using N rather than n), and the data weightings for the DEPM biomass likelihood and the annual age composition likelihood remained unchanged, at 1 and 0.2 respectively. Natural mortality was again estimated by the model, which improved the precision of revised DEPM-derived spawning biomass estimates. However, estimates of total biomass, annual recruitment, and relative depletion over the past two years were less precise, evidenced by high standard deviations, primarily because age composition data for 2025 were not available.

The total biomass estimated by the model in 2024 was 960,000 t (± 121,000 t), increasing to 1,024,000 t (± 317,000 t) in 2025, which is above the estimated total biomass ($B_0$) of 723,000 t (±

109,000 t) for 1992 (i.e., the start of the model time series), representing estimated relative depletion levels of 133% and 142%, respectively. These depletion values greater than 100% suggest that the Sardine population has recovered and expanded beyond the level observed in 1992. However, early biomass estimates are likely less reliable than more recent ones, as DEPM surveys were not conducted until 1995, and earlier surveys are considered less dependable due to the assessment program being in its early stages. While this adds some uncertainty to the exact level of depletion, it appears that the current state of the stock is healthy, with biomass levels comparable to or exceeding those at the commencement of the fishery.

Key uncertainties in this stock assessment include those associated with ageing Sardine from otolith growth increments and the lack of age composition data for 2025. These limitations reduce confidence in the stock status classification. In addition, this assessment incorporates fishery and biological data up to 31 December 2024 and DEPM-based estimates of spawning biomass derived from ichthyoplankton sampling conducted up to April 2025. Consequently, it does not account for potential effects of the recent algal bloom—first occurring in coastal waters off the Fleurieu Peninsula in March 2025, and subsequently expanded to Investigator Strait, Gulf St Vincent and Spencer Gulf from April 2025—on the Australian Sardine stock. Notably, (1) extensive and widespread mortalities of finfish, elasmobranchs, cephalopods, and crustaceans have been reported, but not for Australian Sardine, and (2) substantial changes in fisher behaviour, catches and effort have occurred in 2025 (SARDI unpublished data). Ichthyoplankton sampling for the February–April 2025 DEPM survey was undertaken before the bloom affected surveyed areas. Given the timing, spatial extent, and reported fishery impacts of the algal bloom to date, the bloom may influence stock status for the Southern Australia stock of Australian Sardine, as a small portion of the spawning area (e.g. southern Gulf St Vincent and Investigator Strait) overlap the affected areas and period. However, these impacts have not yet been quantified. Accordingly, future stock assessments must explicitly incorporate any quantified algal bloom effects into stock assessment models and management advice. An assessment of algal bloom impacts on South Australia's fish stocks is scheduled for 2025/26, funded by the South Australian and Australian Governments.

### 6.2 Future directions

Future applications of the DEPM to Sardine off South Australia should continue to adopt the revised methods (see Ward et al. 2021) that have been outlined in this report and are currently being applied (e.g. Grammer et al. 2024a, Ivey et al. 2025). Because future estimates of spawning biomass will be driven primarily by the estimate of spawning area, it will be critical for future surveys to utilise the adaptive sampling implemented since 2014 and cover other areas off South Australia where Sardine are likely to spawn, including waters east of Kangaroo Island. During the 2019 and 2022 DEPM surveys, a second plankton sample was taken in each sampling grid (a random distance from original sampling site). These data have provided an opportunity to investigate uncertainty associated with the estimation of *A*. Preliminary results suggest that estimates of *A* for Sardine can be replicated with considerable precision if using comparable sampling gear (SARDI unpublished data). The application of geostatistical methods around estimates of *A* and $P_0$ is a priority to be investigated in the future.

An extensive adult sampling program conducted in 2024 demonstrated the difficulty of producing reliable estimates of adult reproductive parameters during a single sampling season (Grammer et al. 2024a). The updated all-years reproductive parameters should continue to be used to apply the DEPM in South Australia.

Consideration should also be given to further developing SardEst as a two-sex, multi-zone population model with capability to undertake projections, estimate size/age selectivity, conduct management strategy evaluations and incorporate climate-related data.

Climate plays a critical role in shaping the population dynamics of marine fish (e.g. Sydeman et al. 2015). Environmental factors such as sea surface temperature, ocean currents, and primary productivity directly influence spawning success, larval survival, food availability and stock abundance (Vallin et al. 1999, Robitzch et al. 2016, Jghab et al. 2019). Extreme events, such as marine heatwaves and harmful algal bloom, recently observed in South Australia, can also impact fish populations (Robert et al. 2019). While their specific impacts on Sardine are not yet fully understood, these events may alter the distribution and abundance of adults by modifying their preferred habitat conditions. Climate-driven processes can lead to fluctuations in recruitment and biomass, ultimately affecting the sustainability of the fishery (Ferreira et al. 2023). Therefore, understanding and accounting for climate influences is essential for the effective management and long-term conservation of the South Australian sardine stock.

Under the current harvest strategy, an ecosystem assessment is required every four years (PIRSA 2023) with the first one projected to be delivered in 2026. The assessment should be based on the recommendations and outcomes from Goldsworthy et al. (2011, 2013) and should collect data on key ecological indicator species, update the ecosystem model with new data, and estimate ecological performance indicators.

# 7. REFERENCES

Akselrud, A., Alexander, C., Jensen, P., Kuriyama, P. T., Hill, K. T. and Zwolinski, J. P. 2025. Update assessment of the Pacific sardine resource in 2025 for U.S. management in 2025-2026. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-719. 66 pp.

Barnes, J. T., and T. J. Foreman. 1994. Recent-Evidence for the Formation of Annual Growth Increments in the Otoliths of Young Pacific Sardines (*Sardinops-Sagax*). California Fish and Game **80**:29-35.

Blackburn, M. 1950. Studies on the age, growth, and life history of the sardine *Sardinops neopilchardus* (Steindachner), in Southern and Western Australia. Australian Journal of Marine and Freshwater Research **1**:221-258.

Brodziak, J. K. T., J. N. Ianelli, K. Lorenzen, and R. D. Methot. 2011. Estimating natural mortality in stock assessment applications August 11-13, 2009, Alaska Fisheries Science Center, Seattle, WA.

Brooks, M. E., K. Kristensen, K. J. v. Benthem, A. Magnusson, C. W. Berg, A. Nielsen, and B. M. Bolker. 2017. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. The R Journal **9**:378-400.

Bulman, C. M., S. A. Condie, F. J. Neira, S. D. Goldsworthy, and E. A. Fulton. 2011. The trophodynamics of small pelagic fishes in the southern Australian ecosystem and the implications for ecosystem modelling of southern temperate fisheries. Final report for FRDC project 2008/023., CSIRO Marine and Atmospheric Research. Hobart. 101 pp.

Butler, J. L., M. L. Granados, J. T. Barnes, M. Yaremko, and B. J. Macewicz. 1996. Age composition, growth, and maturation of the Pacific sardine (*Sardinops sagax*) during 1994. California Cooperative Oceanic Fisheries Investigations Reports **37**:152-159.

Checkley, D. M., Alheit, J., Oozeki, Y., & Roy, C. 2009. Climate Change and Small Pelagic Fish. Cambridge University Press.

Checkley, D. M. J., and R. G. R. Asch, R. R. . 2017. Climate, Anchovy, and Sardine. Annual Review of Marine Science **9**:469-493.

Cury, P., A. Bakun, R. J. M. Crawford, A. Jarre, R. A. Quiñones, L. J. Shannon, and H. M. Verheye. 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in “wasp-waist” ecosystems. ICES Journal of Marine Science **57**:603-618.

Daly, K. 2007. The diet and guild structure of the small pelagic fish community in the eastern Great Australian Bight, South Australia. Honours thesis, University of Adelaide.

Dimmlich, W. F., W. G. Breed, M. Geddes, and T. M. Ward. 2004. Relative importance of gulf and shelf waters for spawning and recruitment of Australian anchovy, *Engraulis australis*, in South Australia. Fisheries Oceanography **13**:310-323.

Dimmlich, W. F., and T. M. Ward. 2006. Ontogenetic shifts in the distribution and reproductive patterns ofAustralian anchovy (*Engraulis australis*) by otolith microstructure analysis. Marine and Freshwater Research **57**:373-381.

Dimmlich, W. F., T. M. Ward, and B. W.G. 2009. Spawning dynamics and biomass estimates of Australian anchovy (*Engraulis australis*) in gulf and shelf waters of South Australia. Journal of Fish Biology **75**:1560-1576.

Espinoza, P., A. Bertrand, C. D. van der Lingen, S. Garrido, and B. Rojas de Mendiola. 2009. Diet of sardine (*Sardinops sagax*) in the northern Humboldt Current system and comparison with the diets of clupeoids in this and other eastern boundary upwelling systems. Progress In Oceanography **83**:242-250.

Ferreira, A., Garrido, S., Costa, J. L., Teles-Machado, A., Brotas, V., & Brito, A. C. 2023. What drives the recruitment of European sardine in Atlanto-Iberian waters (SW Europe)? Insights from a 22-year analysis. *Science of the Total Environment*, *881*, 163421.Fletcher, W., and R. Tregonning. 1992. Distribution and timing of spawning by the Australian pilchard (*Sardinops sagax neopilchardus*) off Albany, Western Australia. Marine and Freshwater Research **43**:1437-1449.

Fletcher, W. J., & Tregonning, R. J. 1992. Distribution and timing of spawning by the Australian pilchard (Sardinops sagax neopilchardus) off Albany, Western Australia. *Marine and Freshwater Research*, *43*(6), 1437-1449.

Fletcher, W. J., R. J. Tregonning, and G. J. Sant. 1994. Interseasonal variation in the transport of pilchard eggs and larvae off southern Western Australia. Marine Ecology Progress Series **111**:209-224.

Fletcher, W. J. 1995. Application of the otolith weight-age relationship for the pilchard, *Sardinops sagax neopilchardus*. Canadian Journal of Fisheries and Aquatic Science. **52**:657-664.

Fletcher, W. J., and S. J. Blight. 1996. Validity of using translucent zones of otoliths to age the pilchard *Sardinops sagax neopilchardus* from Albany, western Australia. Marine and Freshwater Research **47**:617-624.

Fletcher, W. J., N. C. H. Lo, E. A. Hayes, R. J. Tregonning, and S. J. Blight. 1996. Use of the daily egg production method to estimate the stock size of western Australian sardines (*Sardinops sagax*). Marine and Freshwater Research **47**:819-825.

Francis, R. I. C. C. 2011. Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences **68**:1124-1138.

Francis, R. I. C. C. 2012. The reliability of estimates of natural mortality from stock assessment models. Fisheries Research 119-120:133-134.

Francis, R. I. C. C. 2017. Revisiting data weighting in fisheries stock assessment models. Fisheries Research **192**:5-15.

Ganias, K. 2012. Thirty years of using the postovulatory follicles method: Overview, problems and alternatives. Fisheries Research **117–118**:63-74.

Gaughan, D. J., W. J. Fletcher, and J. P. McKinlay. 2002. Functionally distinct adult assemblages within a single breeding stock of the sardine, *Sardinops sagax*: management units within a management unit. Fisheries Research **59**:217-231.

Gaughan, D. J., T. I. Leary, R. W. Mitchell, and I. W. Wright. 2004. A sudden collapse in distribution of Pacific sardine (*Sardinops sagax*) off southwestern Australia enables an objective re-assessment of biomass estimates. Fishery Bulletin **102**:617-633.

Goldsworthy, S. D., B. Page, P. J. Rogers, C. Bulman, A. Wiebkin, L. J. McLeay, L. Einoder, A. M. M. Baylis, M. Braley, R. Caines, K. Daly, C. Huveneers, K. Peters, A. D. Lowther, and T. M. Ward. 2013. Trophodynamics of the eastern Great Australia Bight ecosystem: ecological change associated with the growth of Australia's largest fishery. Ecological Monitoring **255**.

Goldsworthy, S. D., B. Page, P. J. Rogers, and T. M. Ward. 2011. Establishing ecosystem based management for the South Austalian Sardine Fishery: developing ecological performance indicators and reference points to assess the need for ecological allocations. Fisheries Research and Development Corporation, SARDI Publication Number F2010/000863-1.

Grammer, G., F. Bailleul, A. Ivey, and J. Smart. 2021. Stock assessment of Australian Sardine (*Sardinops sagax*) off South Australia 2021. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000765-8. SARDI Research Report Series No. 1120. 96pp.

Grammer, G. L., and A. R. Ivey. 2022. Spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2022. Report to PIRSA Fisheries and Aquaculture. Institution: South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000566-12. SARDI Research Report Series No.1152. 27pp.

Grammer, G. L., and A. R. Ivey. 2023. Spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2023. Report to PIRSA Fisheries and Aquaculture. Institution: South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000566-13. SARDI Research Report Series No.1194. 32pp.

Grammer, G. L., T. M. Ward, and L. M. Durante. 2022. Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2019-2021. Report to the Australian Fisheries Management Authority. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000270-11. SARDI Research Report Series No. 1133. 101pp.

Grammer, G. L., Ivey, A. R. and Cheesman, C. 2024a. Spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2024. Report to PIRSA Fisheries and Aquaculture. Institution: South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000566-14. SARDI Research Report Series No.1232. 38pp.

Grammer, G., F. Bailleul, and A. Ivey. 2024b. Stock assessment of Australian Sardine (*Sardinops sagax*) off South Australia 2023. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000765-9. SARDI Research Report Series No. 1208. 105pp.

Grant, W. S., A. M. Clark, and B. W. Bowen. 1998. Why restriction fragment length polymorphism analysis of mitochondrial DNA failed to resolve sardine (*Sardinops*) biogeography: Insights from mitochondrial DNA cytochrome b sequences. Canadian Journal of Fisheries and Aquatic Sciences **55**:2539-2547.

Grant, W. S., and R. W. Leslie. 1996. Late Pleistocene dispersal of Indian-Pacific sardine populations in an ancient lineage of the genus Sardinops. Marine Biology **120**:133-142.

Grift, R. E., A. D. Rijnsdorp, S. Barot, M. Heino, and U. Dieckmann. 2003. Fisheries-induced trends n reaction norms for maturation in North Sea plaice. Marine Ecology Progress Series **257**:247-257.

Hayashi, A., Y. Yamashita, K. Kawaguchi, and T. Ishii. 1989. Rearing method and daily otolith ring of Japanese sardine larvae. Nippon Suisan Gakkaishi **55**:997-1000.

Hilborn, R., & Walters, C. J. (Eds.) 2013. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Springer Science & Business Media.

Hilborn, R., R. O. Amoroso, E. Bogazzi, O. P. Jensen, A. M. Parma, C. Szuwalski, and C. J. Walters. 2017. When does fishing forage species affect their predators? Fisheries Research **191**:211-221.

Hillary, R. 2020. Review of Australian sardine stock assessment. July 2020. CSIRO Oceans & Atmosphere. Hobart. 10p.

Hunter, J. R., and S. R. Goldberg. 1980. Spawning incidence and batch fecundity in northern anchovy, *Engraulis mordax*. Fisheries Bulletin **77**:641-652.

Hunter, J. R., and B. J. Macewicz. 1985. Measurement of spawning frequency in multiple spawning fishes. National Marine Fisheries Services. National Oceanic and Atmospheric Administration Technical Report.

Ivey. A. R., Grammer, G. L. and Earl, J. (2025). Spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2025. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2022/000000-1. SARDI Research Report Series No. 1271. 33pp.

Izzo, C., T. M. Ward, A. R. Ivey, I. M. Suthers, J. Stewart, S. C. Sexton, and B. M. Gillanders. 2017. Integrated approach to determining stock structure: implications for fisheries management of sardine, *Sardinops sagax*, in Australian waters. Reviews in Fish Biology and Fisheries **27**:267-284.

Jghab, A., Vargas-Yáñez, M., Reul, A., García-Martínez, M. D. C., Hidalgo, M., Moya, F., ... & Lamtai, A. (2019). The influence of environmental factors and hydrodynamics on sardine (Sardina pilchardus, Walbaum 1792) abundance in the southern Alboran Sea. *Journal of Marine Systems*, *191*, 51-63.

Johnson, K. F., C. C. Monnahan, C. R. McGilliard, K. A. Vert-pre, S. C. Anderson, C. J. Cunningham, F. Hurtado-Ferro, R. R. Licandeo, M. L. Muradian, K. Ono, C. S. Szuwalski,

J. L. Valero, A. R. Whitten, and A. E. Punt. 2015. Time-varying natural mortality in fisheries stock assessment models: identifying a default approach. ICES Journal of Marine Science **72**:137-150.

Jones, J. B., A. D. Hyatt, P. M. Hine, R. J. Whittington, D. A. Griffin, and N. J. Bax. 1997. Australasian pilchard mortalities. World Journal of Microbiology & Biotechnology **13**:383-392.

Kailola, P. J., M. J. Williams, P. C. Stewart, A. M. Reichelt, and C. Grieve. 1993. Australian Fisheries Resourses. Bureau of Resource Sciences, Department of Primary Industries and Energy and the Fisheries Research and Development Corporation, Canberra.

Kerstan, M. 2000. Estimation of precise ages from the marginal increment widths of differently growing sardine (*Sardinops sagax*) otoliths. Fisheries Research **46**:207-225.

Kristensen, K., A. Nielsen, C. W. Berg, H. Skaug, and B. M. Bell. 2016. TMB: Automatic Differentiation and Laplace Approximation. 70:21.

Lasker, R. 1985. An egg production method for estimating spawning biomass of pelagic fish: Application to the Northern Anchovy, *Engraulis mordax*. National Marine Fisheries Services. National Oceanic and Atmospheric Administration Technical Report.

Le Clus, F., and P. Malan. 1995. Models of temperature-dependent rate of development of pilchard *Sardinops sagax* eggs, to be used in routine procedures for estimating daily egg production. South African Journal of Marine Science **16**:1-8.

Lee, H.-H., M. N. Maunder, K. R. Piner, and R. D. Methot. 2011. Estimating natural mortality within a fisheries stock assessment model: An evaluation using simulation analysis based on twelve stock assessments. Fisheries Research 109:89-94.

Louw, G. G., C. D. Van der Lingen, and M. J. Gibbons. 1998. Differential feeding by sardine *Sardinops sagax* and anchovy *Engraulis capensis* recruits in mixed shoals. South African Journal of Marine Science **19**:227-232.

Mangel, M., and P. E. Smith. 1990. Presence-absence sampling for fisheries management. Canadian Journal of Fisheries and Aquatic Sciences **47**:1875-1887.

McCall, A. D. 1990. Dynamic Geography of Marine Fish Populations. University of Washington Press, Seattle, WA.

McLeay, L. J., B. Page, S. D. Goldsworthy, T. M. Ward, and D. C. Paton. 2009a. Size matters: variation in the diet of chick and adult crested terns. Marine Biology **156**:1765-1780.

McLeay, L. J., B. Page, S. D. Goldsworthy, T. M. Ward, D. C. Paton, M. Waterman, and M. D. Murray. 2009b. Demographic and morphological responses to prey depletion in a crested tern (Sterna bergii) population: can fish mortality events highlight performance indicators for fisheries management? ICES Journal of Marine Science **66**:237-247.

Methot, R. D. 2000. Technical description of the stock synthesis assessment program. NOAA Technical Memorandum. Seattle, Washington.

Neira, F. J., J. M. Lyle, and J. P. Keane. 2009. Shelf spawning habitat of *Emmelichthys nitidus* in south-east Australia - Implications and suitability for egg-based biomass estimation. Estuarine Coastal and Shelf Science **81**:521-532.

Neira, F. J., A. Miskiewicz, and T. Trnski. 1998. Larvae of temperate Australian fishes: laboratory guide for larval fish identification. University of Western Australia Press, Nedlands, W.A.

Newman, S. J., B. S. Wise, K. G. Santoro, and D. J. e. Gaughan. 2023. Status Reports of the Fisheries and Aquatic Resources of Western Australia 2021/22: The State of the Fisheries. Department of Primary Industries and Regional Development, Western Australia. 310pp.

Parker, K. 1985. Biomass model for the egg production method. Pages 5-6 *in* R. Lasker, editor. An egg production method for estimating spawning biomass of pelagic fish: Application to the Northern Anchovy, *Engraulis mordax*. National Marine Fisheries Services. National Oceanic and Atmospheric Administration Technical Report.

Parrish, R. H., R. Serra, and W. S. Grant. 1989. The Monotypic Sardines, Sardina and Sardinops - Their Taxonomy, Distribution, Stock Structure, and Zoogeography. Canadian Journal of Fisheries and Aquatic Sciences **46**:2019-2036.

Pauly, D., and R. S. V. Pullin. 1988. Hatching time in spherical, pelagic, marine fish eggs in response to temperature and egg size. Environmental biology of fishes **22**:261-271.

Picquelle, S., and G. Stauffer. 1985. Parameter estimation for an egg production method of anchovy biomass assessment. National Marine Fisheries Services. National Oceanic and Atmospheric Administration Technical Report.

Pikitch, E., P. D. Boersma, I. L. Boyd, D. O. Conover, P. Cury, T. Essington, S. S. Heppell, E. D. Houde, M. Mangel, D. Pauly, É. Plagányi, K. Sainsbury, and R. S. Steneck. 2012. Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs. Lenfest Ocean Program. Washington, DC. 108 pp. http://www.oceanconservationscience.org/foragefish/.

PIRSA. 2007. Addendum to the management plan for the South Australian pilchard fishery. South Australian fisheries management series, Paper No. 47.

PIRSA. 2014. Management plan for the South Australian commercial marine scalefish fishery. Part B–Management arrangements for the taking of Sardines. Paper number 68.

PIRSA. 2020. Sardine Fishery Operator User Guide January 2021.

PIRSA. 2021. Policy Paper - Managing of under-catch and over-catch in South Australian fisheries. Government of South Australia 2021. 10pp.

PIRSA. 2023. Management Plan for the South Australian Commercial Sardine Fishery. Fisheries Management Series paper number 87. The South Australian Fisheries Management Series. Department of Primary Industries and Regions. Government of South Australia. 49 pp.

Punt, A. E., M. G. Dalton, W. Cheng, A. J. Hermann, K. K. Holsman, T. P. Hurst, J. N. Ianelli, K. A. Kearney, C. R. McGilliard, D. J. Pilcher, and M. Véron. 2021. Evaluating the impact of climate and demographic variation on future prospects for fish stocks: An application for northern rock sole in Alaska. Deep Sea Research Part II: Topical Studies in Oceanography **189-190**:104951.

Quinonez-Velazquez, C., M. O. Nevarez-Martinez, and M. G. Gluyas-Millan. 2000. Growth and hatching dates of juvenile pacific sardine *Sardinops caeruleus* in the Gulf of California. Fisheries Research **48**:99-106.

R Core Team. 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Rice, J. A. 1995. Mathematical Statistics and Data Analysis. Duxbury Press, Belmont, California.

Rijnsdorp, A. D. 1993. Fisheries as a large-scale experiment on life-history evolution: disentangling phenotypic and genetic effects in changes in maturation and reproduction of North Sea plaice, *Pleuronectes platessa* L. Oecologia **96**:391-401.

Roberts, S. D., Van Ruth, P. D., Wilkinson, C., Bastianello, S. S., & Bansemer, M. S. (2019). Marine heatwave, harmful algae blooms and an extensive fish kill event during 2013 in South Australia. *Frontiers in Marine Science*, ***6***, 610.

Robitzch, V. S., Lozano-Cortés, D., Kandler, N. M., Salas, E., & Berumen, M. L. (2016). Productivity and sea surface temperature are correlated with the pelagic larval duration of damselfishes in the Red Sea. *Marine Pollution Bulletin*, *105*(2), 566-574.

Roelofs, A., T. Piddocke, C. Ashby, S. Conron, K. Hartmann, A. Hesp, P. Hone, I. Jacobsen, M. Jesson-Kerr, S. Mayfield, J. Stewart, M. Usher, J. Woodhams, and D. Wright (eds). 2024. Status of Australian Fish Stocks Reports 2024. Fisheries Research and Development Corporation, Canberra.

Rogers, P. J., M. Geddes, and T. M. Ward. 2003. Blue sprat *Spratelloides robustus* (Clupeidae: Dussumieriinae): A temperate clupeoid with a tropical life history strategy? Marine Biology **142**:809-824.

Rogers, P. J., P. Stephenson, L. J. McLeay, W. F. Dimmlich, and T. M. Ward. 2004. Sardine (*Sardinops sagax*). South Australian Research and Development Institute Aquatic Sciences.

Rogers, P. J., and T. M. Ward. 2007. Application of a 'case-building approach' to investigate the age distributions and growth dynamics of Australian sardine (*Sardinops sagax*) off South Australia. Marine and Freshwater Research **58**:461-474.

Schwartzlose, R. A., J. Alheit, A. Bakun, T. R. Baumgartner, R. Cloete, R. J. M. Crawford, W. J. Fletcher, Y. Green-Ruiz, E. Hagen, T. Kawasaki, D. Lluch-Belda, S. E. Lluch-Cota, A. D. MacCall, Y. Matsuura, M. O. Nevárez-Martínez, R. H. Parrish, C. Roy, R. Serra, K. V. Shust, M. N. Ward, and J. Z. Zuzunaga. 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. South African Journal of Marine Science **21**:289-347.

Sexton, S. C., T. M. Ward, and C. Huveneers. 2017. Characterising the spawning patterns of Jack Mackerel (*Trachurus declivis*) off eastern Australia to optimise future survey design. Fisheries Research **186**:223-236.

Sexton, S. C., T. M. Ward, J. Stewart, K. M. Swadling, and C. Huveneers. 2019. Spawning patterns provide further evidence for multiple stocks of sardine (Sardinops sagax) off eastern Australia. Fisheries Oceanography **28**:18-32.

Sippel, T., H. H. Lee, K. Piner, and S. L. H. Teo. 2017. Searching for M: Is there more information about natural mortality in stock assessments than we realize? Fisheries Research 192:135-140.

Smith, A. D. M., C. J. Brown, C. M. Bulman, E. A. Fulton, P. Johnson, I. C. Kaplan, H. Lozano-Montes, S. Mackinson, M. Marzloff, L. J. Shannon, Y.-J. Shin, and J. Tam. 2011. Impacts of fishing low–trophic level species on marine ecosystems. Science **333**:1147-1150.

Smith, A. D. M., T. M. Ward, F. Hurtado, N. Klaer, E. Fulton, and A. E. Punt. 2015. Review and update of harvest strategy settings for the Commonwealth Small Pelagic Fishery: Single species and ecosystem considerations. Final Report of FRDC Project No. 2013/028. CSIRO Oceans and Atmosphere Flagship, Hobart. 74 pp.

Smith, P. E., and S. L. Richardson. 1977. Standard techniques for pelagic fish egg and larva surveys. Food and Agriculture Organisation. Fisheries Technical Paper No. 175. 100 pp.

Somarakis, S., I. Palomera, A. Garcia, L. Quintanilla, C. Koutsikopoulos, A. Uriarte, and L. Motos. 2004. Daily Egg Production of anchovy in European waters. ICES Journal of Marine Science **61**:944-958.

Stratoudakis, Y., Bernal, M., Ganias, K., & Uriarte, A. (2006). The daily egg production method: recent advances, current applications and future challenges. *Fish and Fisheries*, *7*(1), 35-57.

Sydeman, W. J., Poloczanska, E., Reed, T. E., & Thompson, S. A. (2015). Climate change and marine vertebrates. *Science*, ***350***(6262), 772-777.

Thomas, R. M. 1984. A method of age determination for the South West African pilchard *Sardinops ocellata*. South African Journal of Marine Science **2**:63-70.

Thorson, J. T., A. C. Hicks, and R. D. Methot. 2014. Random effect estimation of time-varying factors in Stock Synthesis. ICES Journal of Marine Science 72:178-185.

Thorson, J. T., J. N. Ianelli, S. B. Munch, K. Ono, and P. D. Spencer. 2015. Spatial delay-difference models for estimating spatiotemporal variation in juvenile production and population abundance. Canadian Journal of Fisheries and Aquatic Sciences 72:1897-1915.

Tourre, Y. M., S. E. Lluch-Cota, and W. B. White. 2007. Global multidecadal ocean climate and small-pelagic fish population. Environmental Research Letters, 2: 9pp.

Turner, R. 2023. deldir: Delaunay Triangulation and Dirichlet (Voronoi) Tessellation. R package version 0.1-9. https://cran.r-project.org/web/packages/deldir/index.html.

Vallin, L., Nissling, A., & Westin, L. (1999). Potential factors influencing reproductive success of Baltic cod, Gadus morhua: a review. *Ambio*, 92-99.

Van der Lingen, C. D. 1994. Effect of Particle-Size and Concentration on the Feeding-Behavior of Adult Pilchard *Sardinops sagax*. Marine Ecology-Progress Series **109**:1-13.

Van Der Lingen, C. D. 2002. Diet of sardine *Sardinops sagax* in the southern Benguela upwelling ecosystem. South African Journal of Marine Science **24**:301-316.

Venables, W. N., and B. D. Ripley. 2002. Modern Applied Statistics with S. Fourth Edition. Springer, New York.

Véron, M., E. Duhamel, M. Bertignac, L. Pawlowski, M. Huret, and L. Baulier. 2020. Determinism of temporal variability in size at maturation of srdine *Sardina pilchardus* in the Bay of Biscay. Frontiers in Marine Science **7**.

Waldron, M. 1998. Annual ring validation of the South African sardine *Sardinops sagax* using daily growth increments. South African Journal of Marine Science **19**:425-430.

Ward, T. M., P. Burch, and A. R. Ivey. 2010. South Australian Sardine (*Sardinops sagax*) Fishery: Stock Assessment Report 2010: Report to PIRSA Fisheries. SARDI Aquatic Sciences (Adelaide).

Ward, T. M., P. Burch, and A. R. Ivey. 2012. South Australian Sardine (Sardinops sagax) Fishery: Stock Assessment Report 2012. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Ward, T. M., P. Burch, L. J. McLeay, and A. R. Ivey. 2011. Use of the Daily Egg Production Method for stock assessment of sardine, *Sardinops sagax*; lessons learned over a decade of application off southern Australia Reviews in Fisheries Science **19**:1-20.

Ward, T. M., J. Carroll, G. L. Grammer, C. James, R. McGarvey, J. Smart, and A. R. Ivey. 2018. Improving the precision of estimates of egg production and spawning biomass obtained using the Daily Egg Production Method. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. FRDC project No. 2014/026. 90 pp.

Ward, T. M., G. L. Grammer, A. R. Ivey, J. J. Smart, and R. McGarvey. 2021. Increasing the precision of the daily egg production method; 2020's remix of a 1980's classic. ICES Journal of Marine Science **78**:1177-1195.

Ward, T. M., F. Hoedt, L. McLeay, W. F. Dimmlich, G. Jackson, P. J. Rogers, and K. Jones. 2001a. Have recent mass mortalities of the sardine *Sardinops sagax* facilitated an expansion in the distribution and abundance of the anchovy *Engraulis australis* in South Australia? Marine Ecology-Progress Series **220**:241-251.

Ward, T. M., F. Hoedt, L. McLeay, W. F. Dimmlich, M. Kinloch, G. Jackson, R. McGarvey, P. J. Rogers, and K. Jones. 2001b. Effects of the 1995 and 1998 mass mortality events on the spawning biomass of *Sardinops sagax* in South Australian waters. ICES Journal of Marine Science **58**:830-841.

Ward, T. M., A. R. Ivey, and G. L. Grammer. 2020a. Spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2020. Report to PIRSA Fisheries and Aquaculture., South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000566-11. SARDI Research Report Series No.1074. 27pp.

Ward, T. M., M. Kinloch, J. G.K., and F. J. Neira. 1998. A Collaborative Investigation of the Usage and Stock Assessment of Baitfish in Southern and Eastern Australian Waters, with Special Reference to Pilchards (*Sardinops sagax*). South Australian Research and Development Institute (Aquatic Sciences). Final Report to Fisheries Research and Development Corporation.

Ward, T. M., and L. J. McLeay. 1998. Use of the Daily Egg Production Method to Estimate the Spawning Biomass of Pilchards (*Sardinops sagax*) in Shelf Waters of Central and Western South Australia in 1998. Report to the South Australian Sardine Working Group. South Australian Research and Development Institute Report.

Ward, T. M., and L. J. McLeay. 1999. Spawning biomass of Pilchards (*Sardinops sagax*) in shelf waters of central and western South Australia in 1999 Report to the South Australian Pilchard Working Group.

Ward, T. M., L. J. McLeay, W. F. Dimmlich, P. J. Rogers, S. McClatchie, R. Matthews, J. Kampf, and P. D. Van Ruth. 2006. Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (*Sardinops sagax*), anchovy (*Engraulis australis*) and southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight. Fisheries Oceanography **15**:191-207.

Ward, T. M., P. J. Rogers, P. Stephenson, D. K. Schmarr, N. Strong, and L. J. McLeay. 2005. Implementation of an Age Structured Stock Assessment Model for Sardine (*Sardinops sagax*) in South Australia. Final report to Fisheries Research and Development Corporation.

Ward, T. M., J. Smart, G. L. Grammer, A. Ivey, and R. McGarvey. 2020b. Stock assessment of Australian Sardine (*Sardinops sagax*) off South Australia 2019. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000765-7. SARDI Research Report Series No. 1048. 107 pp.

Ward, T. M., J. Smart, and A. Ivey. 2017. Stock assessment of Australian Sardine (*Sardinops sagax*) off South Australia 2017. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000765-6. SARDI Research Report Series No. 971.:107.

Ward, T. M., and J. Staunton-Smith. 2002. Comparison of the spawning patterns and fisheries biology of the sardine, *Sardinops sagax*, in temperate South Australia and sub-tropical southern Queensland. Fisheries Research **56**:37-49.

Ward, T. M., A. R. Whitten, and A. R. Ivey. 2015. South Australian Sardine (*Sardinops sagax*) Fishery: Stock Assessment Report 2015. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Ward, T. M., B. W. Wolfe, G. L. Grammer, A. R. Ivey, E. King, A. Schiller, K. S. McDonald, and J. M. Dambacher. 2023. Large sardine resource discovered off south-eastern Australia: Potential risks, challenges and benefits of establishing a new fishery. Marine Policy **155**:105739.

Watson, D. F. 1981. Computing the n-dimensional Delaunay tessellation with application to Voronoi polytopes. The Computer Journal. pp167-172.

White, K. V., and W. J. Fletcher. 1998. Identifying the developmental stages for eggs of the Australian pilchard, *Sardinops sagax*. Fisheries Western Australia. Fisheries Research Report No.103.

Whittington, I. D., M. Crockford, D. Jordan, and B. Jones. 2008. Herpesvirus that caused epizootic mortality in 1995 and 1998 in pilchard, *Sardinops sagax* (Steindachner), in Australia is now endemic. Journal of Fish Diseases **31**:97-105.

Wood, S. N. 2006. Generalized Additive Models An Introduction with R. Chapman and Hall/CRC.

Yoneda, M., Yamamoto, M., Yamada, T., Takahashi, M., & Shima, Y. (2015). Temperature-induced variation in sexual maturation of Japanese anchovy Engraulis japonicus. *Journal of the Marine Biological Association of the United Kingdom*, *95*(6), 1271-1276.

# APPENDIX A: ANNUAL ESTIMATES OF SELECTED BIOLOGIAL PARAMETERS

**Table A1.** Annual sex ratio of Sardine for commercial catch samples from all regions between 1995 and 2024. Data were unavailable for 2007 and limited for 2019. Sex ratio was calculated as number of females divided by total number of fish collected per sample.

| Year | Females | Males | Sex Ratio |
|---|---|---|---|
| 1995 | 1248 | 728 | 0.63 |
| 1996 | 1501 | 1048 | 0.59 |
| 1997 | 317 | 251 | 0.56 |
| 1998 | 1088 | 928 | 0.54 |
| 1999 | 1117 | 779 | 0.59 |
| 2000 | 358 | 398 | 0.47 |
| 2001 | 1461 | 929 | 0.61 |
| 2002 | 1662 | 1412 | 0.54 |
| 2003 | 2020 | 1715 | 0.54 |
| 2004 | 1827 | 1477 | 0.55 |
| 2005 | 1601 | 959 | 0.63 |
| 2006 | 608 | 585 | 0.51 |
| 2008 | 1168 | 797 | 0.59 |
| 2009 | 3088 | 2317 | 0.57 |
| 2010 | 4078 | 4152 | 0.50 |
| 2011 | 923 | 929 | 0.50 |
| 2012 | 1003 | 1063 | 0.49 |
| 2013 | 682 | 760 | 0.47 |
| 2014 | 828 | 843 | 0.50 |
| 2015 | 1483 | 1562 | 0.49 |
| 2016 | 1934 | 1622 | 0.54 |
| 2017 | 2005 | 1476 | 0.58 |
| 2018 | 1309 | 1038 | 0.56 |
| 2019 | 59 | 53 | 0.53 |
| 2020 | 692 | 600 | 0.54 |
| 2021 | 986 | 1009 | 0.49 |
| 2022 | 1219 | 931 | 0.57 |
| 2023 | 1533 | 1299 | 0.54 |
| 2024 | 3933 | 3298 | 0.54 |

**Table A2.** Summary of otolith readability index scores for otoliths collected between 1995 and 2024 from commercial and fishery-independent samples.

| | Readability | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Total | | |
| Year | 1 | 2 | 3 | 4 | 5 | GZ | OZ | GSV | Unknown | All |
| 1995 | 0 | 87 | 411 | 159 | 2 | 466 | 193 | 0 | 0 | 659 |
| 1996 | 1 | 145 | 366 | 109 | 10 | 366 | 265 | 0 | 0 | 631 |
| 1997 | 0 | 154 | 275 | 54 | 3 | 390 | 96 | 0 | 0 | 486 |
| 1998 | 18 | 200 | 800 | 262 | 11 | 443 | 792 | 56 | | 1,291 |
| 1999 | 0 | 50 | 546 | 389 | 18 | 591 | 312 | 0 | 100 | 1,003 |
| 2000 | 2 | 82 | 490 | 65 | 2 | 318 | 323 | 0 | 0 | 641 |
| 2001 | 0 | 59 | 1,431 | 689 | 113 | 1627 | 545 | 70 | 50 | 2,292 |
| 2002 | 0 | 53 | 1,527 | 895 | 133 | 1411 | 1197 | 0 | 0 | 2,608 |
| 2003 | 0 | 39 | 1,057 | 229 | 18 | 1113 | 220 | 0 | 10 | 1,343 |
| 2004 | 10 | 121 | 690 | 465 | 265 | 1492 | 59 | 0 | 0 | 1,551 |
| 2005 | 1 | 13 | 301 | 235 | 368 | 778 | 123 | 0 | 17 | 918 |
| 2006 | 0 | 9 | 180 | 135 | 469 | 439 | 337 | 0 | 17 | 793 |
| 2008 | 0 | 9 | 144 | 183 | 303 | 638 | 0 | 0 | 1 | 639 |
| 2009 | 0 | 27 | 314 | 370 | 784 | 1449 | 0 | 12 | 34 | 1,495 |
| 2010 | 4 | 64 | 469 | 577 | 73 | 801 | 239 | 141 | 6 | 1,187 |
| 2011 | 1 | 7 | 111 | 138 | 91 | 173 | 168 | 7 | 0 | 348 |
| 2012 | 0 | 0 | 9 | 14 | 13 | 12 | 24 | 0 | 0 | 36 |
| 2013 | 0 | 15 | 222 | 146 | 143 | 365 | 161 | 0 | 0 | 526 |
| 2014 | 0 | 9 | 253 | 150 | 110 | 450 | 72 | 0 | 0 | 522 |
| 2015 | 0 | 6 | 297 | 184 | 310 | 619 | 178 | 0 | 0 | 797 |
| 2016 | 0 | 33 | 389 | 224 | 127 | 542 | 212 | 19 | 0 | 773 |
| 2017 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2019 | 0 | 2 | 20 | 22 | 10 | 54 | 0 | 0 | 0 | 54 |
| 2020 | 0 | 18 | 230 | 266 | 90 | 558 | 0 | 46 | 0 | 604 |
| 2021 | 0 | 11 | 220 | 270 | 120 | 496 | 53 | 72 | 0 | 621 |
| 2022 | 0 | 31 | 297 | 264 | 136 | 479 | 217 | 32 | 0 | 728 |
| 2023 | 2 | 110 | 487 | 515 | 136 | 795 | 271 | 184 | 0 | 1,250 |
| 2024 | 3 | 236 | 757 | 639 | 196 | 1359 | 96 | 364 | 12 | 1,831 |
| All Years | 42 | 1,590 | 12,293 | 7,648 | 4,054 | 18224 | 6153 | 1003 | 247 | 25,627 |

**Table A3**: Annual and all-years parameters used to calculate estimates of Spawning Biomass. Total *A*: total area sampled (km$^2$), *A*: spawning area (km$^2$); $P_0$: mean daily egg production (egg·m$^{-2}$·day$^{-1}$); *S*: spawning fraction; *R*: sex ratio; *W*: mean female weight (g); $\hat{F}$: batch fecundity (oocytes·batch$^{-1}$); *F'*: Fecundity / Female Weight. Errors around the estimates are standard deviation (SD). N: number of samples; n: number of individuals. *F'* was calculated using the all-years $\hat{F}$ relationship with *W* from that year. Data sources for table: Ward et al. (2021), Ivey et al. (2025).

| Time | Total *A* | *A* | $P_0$ | $P_0$ SD | N.$P_0$ | *S* | *S* SD | N.S | n.S | *R* | *R* SD | N.R | n.R | *W* | *W* SD | N.W | n.W | $\hat{F}$ | $\hat{F}$ SD | N. $\hat{F}$ | n. $\hat{F}$ | *F'* | *F'* SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| All Years | - | - | 88.7 | 4.3 | 7654 | 0.111 | 0.006 | 251 | 17210 | 0.53 | 0.02 | 226 | 30713 | 58.3 | 17.9 | 271 | 17691 | 17967 | 7227 | 271 | 17691 | 308.4 | 0.6 |
| 1998 | 48379 | 32980 | 99.0 | 30.8 | 164 | 0.139 | 0.015 | 12 | 530 | - | - | - | - | 46.5 | 11.2 | 11 | 461 | 14196 | 5365 | 11 | 461 | 305.0 | 3.9 |
| 1999 | 65956 | 15637 | 50.0 | 14.9 | 213 | 0.179 | 0.020 | 16 | 715 | - | - | - | - | 52.4 | 13.0 | 17 | 738 | 15879 | 5692 | 17 | 738 | 303.3 | 3.1 |
| 2000 | 102198 | 38658 | 52.9 | 12.7 | 290 | 0.158 | 0.012 | 15 | 1012 | 0.52 | 0.05 | 15 | 2179 | 49.2 | 12.2 | 16 | 1032 | 14664 | 5484 | 16 | 1032 | 298.3 | 2.6 |
| 2001 | 132382 | 39131 | 59.7 | 15.6 | 316 | 0.179 | 0.014 | 10 | 743 | 0.56 | 0.04 | 10 | 1397 | 50.7 | 9.1 | 11 | 1002 | 15765 | 5138 | 11 | 1002 | 310.7 | 2.7 |
| 2002 | 131574 | 37462 | 97.4 | 29.1 | 319 | 0.077 | 0.014 | 23 | 1631 | 0.60 | 0.04 | 23 | 2932 | 61.8 | 19.5 | 22 | 1836 | 19289 | 7749 | 22 | 1836 | 312.1 | 1.8 |
| 2003 | 133058 | 42905 | 113.5 | 27.4 | 320 | 0.103 | 0.009 | 8 | 435 | 0.48 | 0.03 | 8 | 986 | 52.4 | 8.5 | 8 | 435 | 16348 | 4796 | 8 | 435 | 312.1 | 3.9 |
| 2004 | 105621 | 40219 | 145.3 | 41.3 | 284 | 0.166 | 0.016 | 10 | 412 | 0.52 | 0.03 | 10 | 879 | 78.7 | 16.2 | 10 | 413 | 24242 | 7673 | 10 | 413 | 308.0 | 3.7 |
| 2005 | 122831 | 42142 | 59.5 | 14.3 | 334 | 0.100 | 0.019 | 33 | 2223 | 0.51 | 0.04 | 33 | 4827 | 73.9 | 16.0 | 33 | 2228 | 22642 | 7435 | 33 | 2228 | 306.5 | 1.6 |
| 2006 | 119038 | 50121 | 102.4 | 26.5 | 341 | 0.095 | 0.018 | 20 | 1332 | 0.59 | 0.04 | 20 | 2445 | 63.1 | 21.8 | 21 | 1335 | 19362 | 8285 | 21 | 1335 | 306.8 | 2.2 |
| 2007 | 119036 | 50972 | 104.9 | 27.1 | 341 | 0.130 | 0.019 | 20 | 1084 | 0.54 | 0.06 | 20 | 2244 | 71.1 | 16.8 | 21 | 1084 | 21940 | 7342 | 21 | 1084 | 308.8 | 2.3 |
| 2009 | 119031 | 55179 | 66.3 | 14.1 | 340 | 0.156 | 0.022 | 19 | 1537 | 0.36 | 0.03 | 9 | 2425 | 59.9 | 13.3 | 19 | 1536 | 18059 | 6251 | 19 | 1536 | 301.6 | 2.0 |
| 2011 | 119449 | 44245 | 51.5 | 15.4 | 340 | 0.044 | 0.006 | 14 | 1169 | 0.65 | 0.05 | 13 | 1798 | 46.8 | 12.3 | 15 | 1171 | 14793 | 5570 | 15 | 1171 | 316.2 | 2.5 |
| 2013 | 119297 | 37953 | 39.0 | 8.7 | 340 | 0.072 | 0.017 | 9 | 703 | 0.69 | 0.02 | 9 | 1089 | 51.3 | 12.3 | 9 | 721 | 15995 | 5836 | 9 | 721 | 312.1 | 3.2 |
| 2014 | 125249 | 73981 | 92.7 | 20.0 | 355 | 0.041 | 0.006 | 16 | 886 | 0.57 | 0.02 | 16 | 1574 | 47.9 | 13.9 | 16 | 861 | 15046 | 6065 | 16 | 861 | 314.3 | 3.0 |
| 2016 | 122598 | 50551 | 47.7 | 9.9 | 350 | 0.088 | 0.013 | 9 | 656 | 0.65 | 0.03 | 9 | 1088 | 49.7 | 17.3 | 9 | 679 | 15561 | 6863 | 9 | 679 | 312.8 | 3.4 |
| 2017 | 119661 | 66453 | 136.3 | 25.8 | 343 | 0.120 | 0.019 | 8 | 504 | 0.53 | 0.04 | 8 | 1030 | 59.6 | 12.3 | 9 | 511 | 18518 | 6321 | 9 | 511 | 310.9 | 3.7 |
| 2018 | 120043 | 63215 | 112.4 | 24.6 | 343 | 0.054 | 0.009 | 9 | 714 | 0.70 | 0.04 | 9 | 1026 | 46.5 | 7.2 | 9 | 718 | 14610 | 4500 | 9 | 718 | 314.1 | 3.1 |
| 2019 | 119369 | 53600 | 68.1 | 16.3 | 339 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2020 | 129700 | 82627 | 94.0 | 18.4 | 379 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2022 | 129982 | 76842 | 97.6 | 19.0 | 381 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2023 | 136471 | 66248 | 93.8 | 26.1 | 403 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2024 | 137679 | 61471 | 152.6 | 33.2 | 405 | 0.162 | 0.022 | 14 | 924 | 0.37 | 0.06 | 14 | 2794 | 55.6 | 16.3 | 15 | 930 | 17178 | 6800 | 15 | 930 | 309.0 | 2.7 |
| 2025 | 140900 | 114640 | 101.3 | 17.4 | 414 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

# APPENDIX B: MODEL SPECIFICATIONS

This section describes the components of the SardEst model fitted in TMB. The likelihood function includes three components: 1) Estimates of spawning biomass from DEPM surveys, 2) age-compositions, and 3) deviations around mean annual recruitment ($\bar{R}$).

The model is age-structured with recruitment occurring at age one. The age index (*a*) therefore extends from 1 to 8+ with the final age-class forming a plus group ($a_{max}$).

## Biological Parameters

$$P_a = 1*(1+e^{-\log(19)*(a-a_{50})/(a_{95}-a_{50})})^{-1}$$

where $P_a$ is the proportion mature at age *a*, $a_{50}$ is the age where 50% of the population is mature and $a_{95}$ is the age where 95% of the population is mature

$$W_a = A*(l_a)^B$$

where *A* and *B* are the scalar and power parameters of the length-weight relationship for both sexes, respectively.

Growth, as (caudal fork) length $l_a$ versus age, was assumed to follow a von Bertalanffy curve calculated as:

$$l_a = l_\infty - (l_\infty - l_0)*e^{(-k*a)}$$

where $l_\infty$ is the asymptotic length, $l_0$ is the length at age zero, and *k* is the growth coefficient.

## Selectivity

The selectivity-at-age was determined as a double normal function, which describes dome-shaped selectivity and was originally fitted in Stock Synthesis (Ward et al. 2015, 2017, 2020b). There are three components to the function: an ascending limb, a descending limb and a plateau, which are connected by steep logistic joiners that provide differentiability.

Selectivity-at-age *a* is calculated as

$$S_a = asc_a\left(1-j_{1,a}\right)+j_{1,a}\left(\left(1-j_{2,a}\right)+j_{2,a}dsc_a\right)$$

where the joiner functions are:

$$j_{1,a} = 1 / \left( 1 + e^{\left( -20 \frac{a-\beta_1}{1+(a-\beta_1)} \right)} \right)$$

and

$$j_{2,a} = 1 / \left( 1 + e^{\left( -20 \frac{a-peak_2}{1+(a-peak_2)} \right)} \right)$$

and the ascending and descending limbs are:

$$\text{asc}_a = \left(1+e^{-\beta_5}\right)^{-1} + \left(1 - \left(1+e^{-\beta_5}\right)^{-1}\right) \frac{e^{\left(\frac{-(a-\beta_1)^2}{e^{\beta_3}}\right)^2} - t1_{\min}}{1 - t1_{\min}}$$

$$dsc_a = 1 + \left(\left(1+e^{-\beta_6}\right)^{-1} - 1\right) \frac{e^{\left(\frac{-(a-peak_{2,})^2}{e^{\beta_4}}\right)}}{t2_{\min} - 1}.$$

*ß₁* is the age where selectivity = 1.0 begins, *ß₂* is age where selectivity = 1.0 ends, *ß₃* determines the slope of the ascending limb (this is the width of the top, $peak_2$ is the endpoint), *ß₄* determines the slope of the descending limb, *ß₅* is the selectivity at age-at-recruitment and *ß₆* is the selectivity at $a_{max}$. $t1_{min}$ and $t2_{min}$ are defined as:

$$t1_{\min} = e^{\left(-\frac{(a_{\min}-\beta_1)^2}{e^{\beta_3}}\right)}$$

$$t2_{\min} = e^{\left(-\frac{(a_{\max}-peak_2)^2}{e^{\beta_3}}\right)}.$$

$peak_2$ is the endpoint where selectivity = 1.0, while

$$peak_2 = \beta_1 + 1 + \left( \frac{0.99 a_{\max} - \beta_1 - 1}{1 + e^{-\beta_2}} \right).$$

## Recruitment

Annual recruitment is fit using a lognormal distributed recruitment deviates around a mean number of recruits:

$$R_t = \bar{R} * \exp\left(\log(\tilde{R}_t)\right)$$

where $\tilde{R}_t$ are fitted as random effects with $\sigma_R$ as the standard deviation among recruitment deviations.

$$\log(\tilde{R}_t) = N(0;\sigma_R^2)$$

## Population dynamics

*Starting numbers-at-age*

Because exploitation was nearly zero prior to the first year of data, initial numbers-at-age are determined from the estimated recruitment at time zero (*$R_0$*) and the estimated rate of natural mortality (*M*):

$$N_{0,a} = \begin{cases} R_0 & \text{for } a = 1 \\ N_{0,a-1} * e^{-M} & \text{for } a > 1 \end{cases}.$$

*Population with fishing mortality*

Sardine population numbers $N_{t+1,a}$ at age $a$ having recruited that year or undergone survival from start of year $t$ to start of year $t+1$ are written

$$N_{t+1,a} = \begin{cases} R_{t+1} & \text{for } a = 1 \\ N_{t,a-1} * e^{-Z_{t,a-1}} & 2 \le a \le a_{\max} - 1 \\ N_{t,a-1} * e^{-Z_{t,a-1}} + N_{t,a} * e^{-Z_{t,a}} & \text{for } a = a_{\max} \end{cases}$$

where survival to the plus group occurs from both the plus group and the age below, and where $Z_{t,a}$ is the total instantaneous mortality rate at age $a$ over year $t$,

$$Z_{t,a} = M + (F_t * S_a),$$

and where $F_t$ is the fishing mortality rate over year $t$, determined using the hybrid fishing mortality method.

The hybrid fishing method allows the full *F* ($F_t$) to be tuning coefficients to match predicted catch ($\hat{C}_t$) to observed catch ($C_t^{obs}$), rather than full estimated parameters. Pope's approximation is used to determine the initial (first iteration) harvest rate, which is used as the initial Baranov continuous *F*. These values of *F* are then tuned over a series of iterations (approximately five) until the resulting predicted catch matches observed catch for each corresponding *F*:

$$temp_{1,t} = \frac{C_t^{obs}}{B_t + 0.1C_t^{obs}}$$

$$j_{1,t} = \left(1 + e^{\left(30\left(temp_{1,t} - 0.95\right)\right)}\right)^{-1}$$

$$F_{1,t} = \frac{-\ln\left(1 - (j_{1,t}temp_{1,t} + 0.95\left(1 - j_{1,t}\right))\right)}{\delta}$$

where $\delta$ = 1.0 for the duration of the season, $B_t$ is the estimated biomass in year *t, and* $j_{1,t}$ is a logistic joiner that prevents the initial values of *F* from exceeding 0.95yr$^{-1}$.

Catch in numbers for year *t* at age *a* is:

$$C_{t,a} = \frac{F_t}{Z_{t,a}^{'}}\left(S_a N_{t,a}\right)\lambda_{t,a}$$

where $\lambda_{t,a}$ is survivorship in year *t* at age *a*:

$$\lambda_{t,a} = 1 - \mathrm{e}^{\left(-\delta Z_{t,a}\right)} / Z_{t,a}.$$

Estimated catch in weight in year *t* is estimated as:

$$\hat{C}_t = \sum_a \frac{F_{1,t,}}{Z_{t,a}}\left(W_a N_{t,a} S_{,a}\right)\lambda_{t,a}.$$

An adjustment is made to yearly $Z_t^{adj}$ in each iteration based on how closely predicted catch matches observed catch:

$$Z_t^{adj} = \frac{C_t^{obs}}{\hat{C}_t + 0.0001}$$

This adjustment is then applied to all *F*'s and $Z_{t,a}$ and $\lambda_{t,a}$ are tuned.

$$Z_{t,a} = M + Z_{t,a}^{adj}\left(Z_{t,a} - M\right)$$

$$\lambda_{t,a} = \left(1 - \mathrm{e}^{\left(-\delta Z_{t,a}\right)}\right) / \left(Z_{t,a}\right).$$

This adjusted mortality rate is then used to calculate a new value for total catch and the new *F* estimate is the ratio of this value to observed catch:

$$temp_{2,t} = \sum_a \left(W_a N_{t,a} S_a\right)\lambda_{t,a}$$

$$F_{2,t} = \frac{C_t^{\mathrm{obs}}}{temp_{2,t} + 0.0001}.$$

A second joining function prevents any *F* from exceeding a maximum value $F_{max}$:

$$j_{2,t} = \left(1 + \exp^{30\left(F_{2,t} - 0.95 * F_{\max}\right)}\right)^{-1}.$$

The final updated $F_t$ are calculated as:

$$F_t = j_{2,t}F_{2,t} + \left(1 - j_{2,t}\right)F_{\max}.$$

Spawning stock biomass was calculated as the proportion of the population that was mature:

$$\hat{G}_t = \sum_a W_a P_a N_{t,a}.$$

Total biomass was calculated as the total weight of the population:

$$B_t = \sum_a W_a N_{t,a}.$$

Proportional age-composition was calculated as:

$$\hat{p}_{t,a} = \hat{C}^{W}_{t,a} \sum_{a} \hat{C}^{W}_{t,a} \ .$$

## Likelihoods

The probability of the recruitment deviates were estimated as lognormal random effects around mean recruitment ( $\bar{R}$ ) as:

$$L_{\tilde{R}} = \sum_{t} \log(\sigma_R) + 0.5*(\log(R_t) - \log(\bar{R}))^2 / \sigma_R^2 \ .$$

The proportional age-compositions were fit using a multinomial likelihood:

$$L_p = -\sum_{t,a} n_t p_{t,a} * \log(\hat{p}_{t,a})$$

where $p_{t,a}$ is the proportional age composition data in year $t$ for age $a$ and $n_t$ was the sample size in year $t$.

Estimated spawning stock biomass was fit to the DEPM estimates as:

$$L_I = \sum_{t} 0.5 \cdot \log(\sigma_t^2) + \frac{\left[\log(I_t) - \left(\log(\hat{G}_t) - \sigma_t^2 / 2\right)\right]^2}{2\sigma_t^2}$$

where $I_t$ is the DEPM estimate of spawning stock biomass in year $t$, and where the lognormal likelihood $\sigma_t^2$ parameter for each year can be written in terms of the coefficient of variation, $Cv_t^2$ , obtained for each yearly spawning biomass estimate from the DEPM survey analysis as $\sigma_t^2 = \log(Cv_t^2 + 1)$.

The catch likelihood was estimated as:

$$L_c = \tfrac{1}{2\sigma_C^2} \sum_{y} \left(\log \hat{C}_t - \log C_t^{\text{obs}}\right)^2$$

where $\sigma_c$ is the standard deviation of the logs of the catches in weight, assumed to be 0.05 so as penalise any substantial difference between $\hat{C}_t$ and $C_t^{obs}$.

The joint likelihood function was the sum of the four likelihood components with weightings of 1 ( $\lambda_I$ ) and 0.2 ( $\lambda_p$ ) applied to the DEPM and age-composition data, respectively:

$$L(\theta \mid D) = L_I * \lambda_I + L_p * \lambda_p + L_{\tilde{R}} + L_c \, .$$